Final Technical Report

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Durability Test Results of Three Non-Road Tier II Diesel Engines Operating on 10% Ethanol-90% Diesel Blend

By

William E. Mitchell

Final Report

Prepared for:

Department of Energy
National Corn Growers
Illinois Corn Growers
Illinois Department of Commerce and Economic Opportunity

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FORWARD

This report presents the results of the durability testing portion of a research program designed to advance the knowledge base of ethanol/diesel fuel blends. The knowledge gained is intended for eventual advancement of a commercialized ethanol/diesel blend fuel supply.

The durability portion of the program was initially funded by the Illinois Department of Commerce and Economic Opportunity (DCEO), Illinois Corn Growers Association (ICGA), and contributing individual Corn Grower State Associations. The durability program started January 2004 and ended September 2006. The Department of Energy Earmark funding joined with the previously listed sponsors on 01 May 2004.

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Recipient: National Corn Growers Association (NCGA)
Project Locations: E. Moline, Illinois, San Antonio, Texas, Waterloo, Iowa

Subcontractors: Southwest Research Institute (SwRI) and William E. Mitchell (WM Consulting, Inc.)
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The research program testing results reported herein was conducted by the Department of Engine and Emissions Research (DEER) of the Southwest Research Institute (SwRI).

ABSTRACT

Three non-road Tier II emissions compliant diesel engines manufactured by John Deere were placed on a durability test plan of 2000 hours each at full load, rated speed (FLRS). The fuel was a blend of 10% fuel ethanol and 90% low sulfur #2 diesel fuel. Seven operational failures involving twenty seven fuel system components occurred prior to completion of the intended test plan.

Regulated emissions measured prior to component failure indicated compliance to Tier II certification goals for the observed test experience.

The program plan included operating three non-road Tier II diesel engines for 2000 hours each monitoring the regulated emissions at 500 hour intervals for changes/deterioration. The program was stopped prematurely due to number and frequency of injection system failures.

The failures and weaknesses observed involved injector seat and valve wear, control solenoid material incompatibility, injector valve deposits and injector high pressure seal cavitation erosion.

Future work should target an E diesel fuel standard that emphasizes minimum water content, stability, lubricity, cetane neutrality and oxidation resistance. Standards for fuel ethanol need to require water content no greater than the base diesel fuel standard. Lubricity bench test standards may need new development for E diesel.

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Introduction

The E diesel Research program was conceived to explore and document the benefits and challenges of blending ethanol and diesel fuel. Progress toward commercialization of an ethanol/diesel fuel blend in the non-road fuel supply was the intended goal.
Previous exploratory emissions and short term durability work had occurred in automotive and on-highway heavy duty diesels but little in the non-road sector.

The Illinois Corn Growers Association (ICGA) and the Illinois Department Commerce and Economic Opportunity (DCEO) contacted John Deere proposing a co-operative research program involving John Deere engines and vehicles and ethanol/diesel fuel blends.

A research program plan was agreed to as follows:

- Regulated and unregulated emissions evaluation
- Lab durability engine tests
- Lab and field vehicle fleet testing

The regulated and unregulated emissions' testing was completed and the results reported in March 2004.

The engine lab durability testing portion was started in February 2004 using the 8.1 Liter engine. Testing of the 12.5 Liter engine started June 2004 and 6.8 Liter engine started test in July 2005.

The DOE earmark funding joined the ICGA and DCEO as co-sponsor as of 01 May 2004 under the project title "The John Deere E diesel Test and Research Project". The Award Number was DE-FG36-04GO14216.

Objectives and Approach

The engine lab durability tests were designed to discover weaknesses in the components and areas of the engine in contact with the fuel and related combustion processes. The full load, rated speed (FLRS) tests have historically provided an acceleration factor of 3-4:1 overall comparing lab testing to customer usage.
The FLRS test was combined with a regulated emissions check every 500 hours. The emissions tests were conducted with the required Certification diesel fuel while the durability test hours were accumulated with E10 diesel comprised of 10% fuel ethanol, an additive treat rate of 1-1.77% as specified by the additive supplier and the remainder 88.23-89% market available #2 low sulfur diesel fuel from the San Antonio area. The fuel ethanol and ethanol blends were stored under a nitrogen blanket and the blended fuels were continuously re-circulated during test operation usage.

A full range of engine data was collected hourly, concentrating on power and fuel rate for the hours accumulated between emissions tests.

The nominal rated power @ speed for the test engines were:

- **6.8Liter**
  129 kW @ 2000 rpm

- **8.1 Liter**
  224 kW @ 2200 rpm

- **12.5 Liter**
  375 kW @ 2100 rpm

All power data observed at John Deere and SwRI were within 2% of nominal power ratings operating on #2D Certification fuel at beginning of test.

Based on the previous emissions testing, the 6.8 Liter and the 12.5 Liter engines were expected to operate on E10 diesel at 92% of rated #2D power. This observed power loss is attributed to reduced energy content of ethanol versus #2Diesel and the lower viscosity of the E10 diesel blend causing more internal injection system leakage.
Conversely, the 8.1 Liter engine demonstrated 98% of rated #2D power operating on E10 diesel due to the unique hydraulic characteristics of the common rail fuel system. (Lower viscosity allows more fuel to be pumped through a given size orifice at a constant pressure)

Work Plan

Table I__ Durability Test Procedure

1) Conduct regulated emissions test w/ Certification fuel
2) Operate Test Engine at Full Load, Rated Speed(FLRS) for 500 hours on E10 diesel
3) Repeat Step #1 Regulated Emissions Test
4) Repeat Step #2 for 500-1000 hours
5) Repeat Step #1 Regulated Emissions Test
6) Repeat Step #2 for1000- 1500 hours
7) Repeat Step #1 Regulated Emissions Test
8) Repeat Step #2 for1500- 2000 hours
9) Repeat Step #1 Regulated Emissions Test

Table II__ Test Engines, Fuel Systems and Operating Conditions

Properties	**6.8 Liter**	**8.1 Liter**	**12.5 Liter**
Engine Model	6068H	6081HRW28	6125HRW02
Serial Number	68EPX000098	6081H213451	6125H012204
Displacement, Liters	6.8	8.1	12.5
Rated Speed, rpm	2000	2200	2100
Rated Power, kW(hp)	129(173)	224(300)	375(503)
Intermediate Speed, rpm	1400	1400	1500
Peak Torque, N-m (lb-ft)	725(535)	1361(1004)	1989(1467)
Inlet Restriction, kPa(in. water)	2.99(12)	2.99(12)	2.99(12)
Exhaust Restriction, kPa (in. mercury)	7.45(2.2)	7.45(2.2)	7.45(2.2)
Turbocharged/ Inter-cooled	Yes/Yes	Yes/Yes	Yes/Yes
Inter-cooling Type	A-T-A	A-T-A	A-T-A
Inter-cooler Outlet Temperature, C(F)	60(140)	60(140)	60(140)
Inter-cooler delta P, kPa (in. water)	12.45(50)	12.45(50)	12.45(50)
Injection System Type- ECU Control	Rotary Pump Line Nozzle	Common Rail	Electronic Unit Injector

Test Fuels

Table III - Durability Test Additive Blending Table

Supplier	Blend (Ethanol % Concentration)	Additive Treat Rate, % vol	Cetane Improver (2-EHN) Treat Rate, % vol
Additive A	7.7	0.6	-
	10	1.0	-
	15	1.0	0.135
Additive C	7.7	1.37	-
	10	1.77	-
	15	2.75	-

Table IV - Durability Test Fuel Ethanol Properties

Test Fuel Ethanol

			EM-4889-F TK22E	EM-4889-F TK24E
Specifications	**Methods**	**Units**	**Results**	**Results**
Acidity	D1613	gKOH/g	0.0283	0.0562
Chloride	D5827	ppm	<1	<1
Specific Gravity @60F	D4052		0.7927	0.7936
API Gravity @60F	D4052		47	46.8
Density @ 15C	D4052	g/L	792.3	793.2
Water Content	D6304	ppm	6623	7197
pHe	D6423		7.57	7.68
Existent Gums				
Unwashed Weight	D381	mg/100mL	3.0	7.0
Washed Weight	D381	mg/100mL	1.0	5.0

Table V E diesel Test Fuel Properties

	2D	2D	2D 4970 Cert	EM 5374F/Add C	EM 5089F/Add C	EM 5046F Add A
Ethanol % D5501	0	0	0	10.7/11.03	7.98/8.13	10 Nom
Cloud Pt C D2500					-6	15
Water , ppm D6304				913/911	2305	
Viscosity, cSt D445@40C	2.146	2.121	2.383		1.891/1.881/1.877	
Cetane Number D613					45.4	
Flash Pt., C D93					37	
HFRR mm wear scar D6079				0.395	0.43	0.295
BOCLE Scuff, gm D6078					3650	6850
Sp. Gravity D4052	0.8333	0.8407	0.8403	0.8291	0.8354/0.8351/0.8266	
Net Heat of Combustion, Btu/Lb	18494	18428	18459		17696/17885	
Sulfur, ppm D2622					70	23

Results

6.8 Liter Engine

Table VI - 6.8L Engine Test Power and Fuel Rate – Start Test 13 July 2005

Hours	HP	kW	#/HR	Kg/Hr
0	158	117.8225	58.5	26.5356
98	155	115.5853	57.5	26.082
100	130	96.94258	58.9	26.71704
200	164	122.2967	59.8	27.12528
300	162	120.8053	60.1	27.26136
400	155	115.5853	60.1	27.26136
500	162	120.8053	60	27.216
501	171	127.5167		
600	171	127.5167		
700	171	127.5167		
800	172	128.2624		
900	171	127.5167		
1000	169	126.0253		
1001	177	131.9910		
1100	170	126.7710		
1200	163	121.5510		
1300	156	116.3310		
1356	129	96.19686	53.9	24.44904

Graph I - 6.8 liter Engine Test Power and Fuel Rate

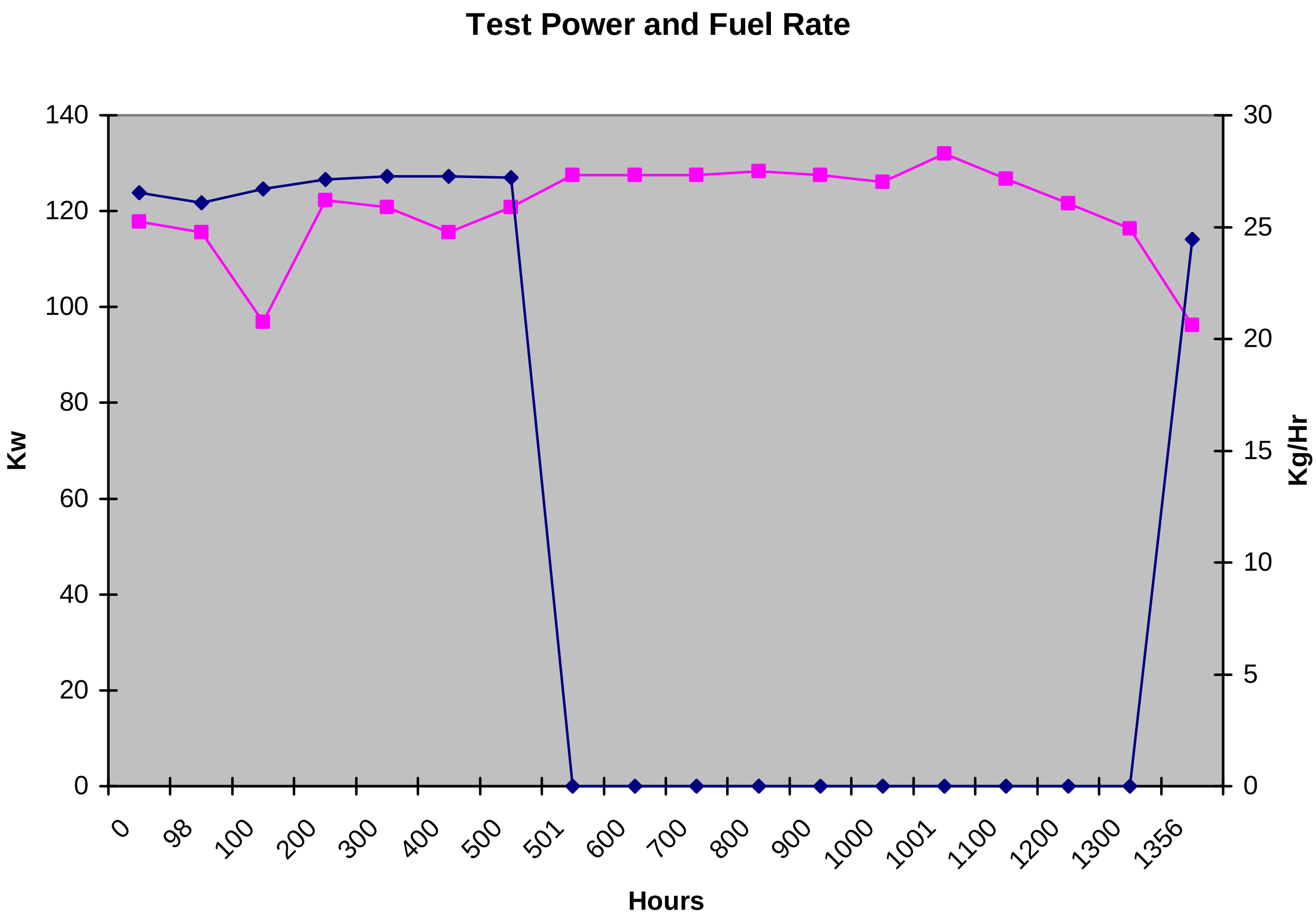


Table VII - 6.8L Engine Durability Emissions Test Results - 0,500, 1000 hours

0 Hour Durability							
	Parameter	Units				**Average**	
8-mode	HC	g/hp-hr				0.3290	
	CO	g/hp-hr				0.6060	
	Nox	g/hp-hr				3.8210	
	PM	g/hp-hr				0.1670	
	CO2	g/hp-hr				515	
	FC	lb/hp-hr				0.3580	
FTP Smoke	A					8.7500	
	B					2.5100	
	C					17.5600	
500 Hour Durability, Test Cell 3							
	Parameter	Units	**68-500-1**	**68-500-2**	**68-500-3**	**Average**	**CV**
8-mode	HC	g/hp-hr	0.27	0.27	0.27	0.27	0.0%
	CO	g/hp-hr	0.59	0.59	0.57	0.58	2.0%
	Nox	g/hp-hr	4.00	3.93	4.03	3.99	1.3%
	PM	g/hp-hr	0.163	0.155	0.161	0.160	2.6%
	CO2	g/hp-hr	513	516	516	515	0.3%
	FC	lb/hp-hr	0.357	0.359	0.359	0.358	0.3%
FTP Smoke	A		10.13	10.30	10.60	10.45	2.0%
	B		2.72	2.29	2.14	2.38	12.6%
	C		21.82	22.89	22.15	22.29	2.5%
1000 Hour Durability, Test Cell 11							
	Parameter	Units	**68-1000-1**	**68-1000-2**	**68-1000-3**	**Average**	**CV**
8-mode	HC	g/hp-hr	0.24	0.26	0.25	0.25	4.0%
	CO	g/hp-hr	0.51	0.49	0.50	0.50	2.0%
	Nox	g/hp-hr	3.75	4.00	3.80	3.85	3.4%
	PM	g/hp-hr	0.131	0.122	0.130	0.128	3.9%
	CO2	g/hp-hr	514	516	512	514	0.4%
	FC	lb/hp-hr	0.358	0.359	0.356	0.358	0.4%
FTP Smoke	A		13.32	12.97	14.07	13.45	4.2%
	B		3.28	2.12	2.52	2.64	22.3%
	C		24.16	25.22	26.28	25.22	4.2%

Event Listing 0-500 Hours

- Started test 13 July 2005
- Power loss caused by #5 injector tip failure @ 97 hours; replaced #5 injector
- Test cell fire caused by ruptured test cell fuel return line @ 170 hours
- Power loss caused by #4 injector tip failure @ 177 hours; replaced all injectors

Results (cont'd)

Figure I - 6.8L Engine #5 Injector Tip Failure

Event Listing 500-1000 Hours

- Uneventful

Event Listing 1000- 1356 (end)

- Power loss/ hard starting; diagnosed faulty fuel control solenoid
- Terminated test 09 February 2006

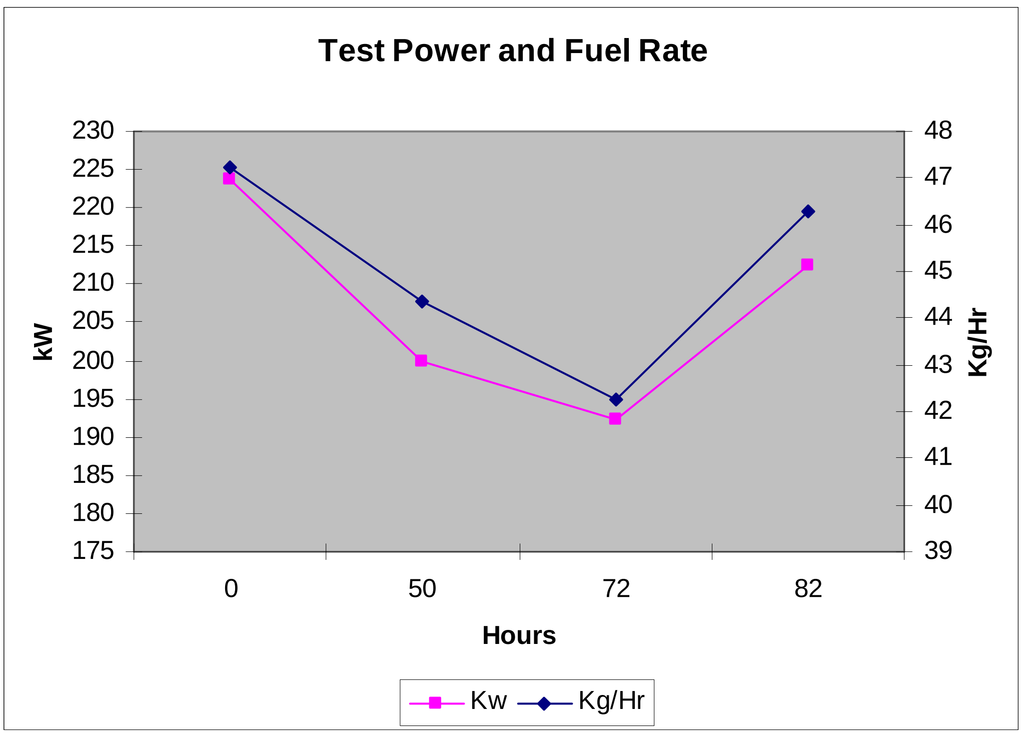
8.1 Liter Engine

Table VIII– 8.1 Liter Test Power and Fuel Rate – Run #1

8.1 Liter Engine Test power and Fuel Rate 1st Run 10 March - 12 April 04

Hours	HP	Kw	#/HR	Kg/Hr	
0	300	223.7136	104.1	47.21976	
50	268	199.8509	97.8	44.36208	
72	258	192.3937	93.2	42.27552	
82	285	212.528	102	46.2672	New Injectors

Graph II- 8.1 Liter Test Power and Fuel Rate – Run #1



Event Listing – Run #1 0- 72 Hours

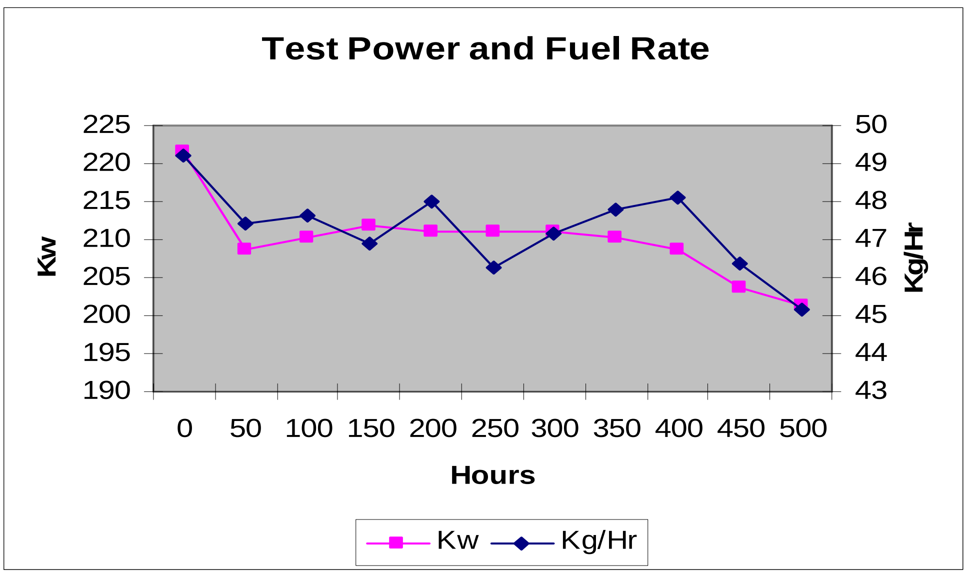
- Started durability test on 10 March 2004; Fuel blend additive A
- Power loss @ 72 hours; diagnosed as malfunctioning injectors; terminated test

Table IX - 8.1 Liter Test Power and Fuel Rate – Run #2

8.1 Liter Engine Test power and Fuel Rate 2nd Run 05 November04-06 December 04

Hours	HP	Kw	#/HR	Kg/Hr	
0	297	221.4765	108.5	49.2156	
50	280	208.7994	104.5	47.4012	
100	282	210.2908	105	47.628	
150	284	211.7823	103.4	46.90224	
200	283	211.0365	105.8	47.99088	
250	283	211.0365	102	46.2672	
300	283	211.0365	104	47.1744	
350	282	210.2908	105.3	47.76408	
400	280	208.7994	106	48.0816	
450	273	203.5794	102.2	46.35792	
500	270	201.3423	99.5	45.1332	EOT

Graph III- 8.1Liter Engine Test Power and Fuel Rate – Run #2



Event Listing – 8.1 Liter Run #2 0 – 500 hours

- Restarted test 02 November 2004 with new injectors and fuel blend with Additive C
- Hard starting reported 440- 500 hours
- could not develop acceptable power for emissions test; diagnosed malfunctioning injectors
- Terminated test on 06 December 2004

Figure II- 8.1 Liter Injector Command Piston Scuff

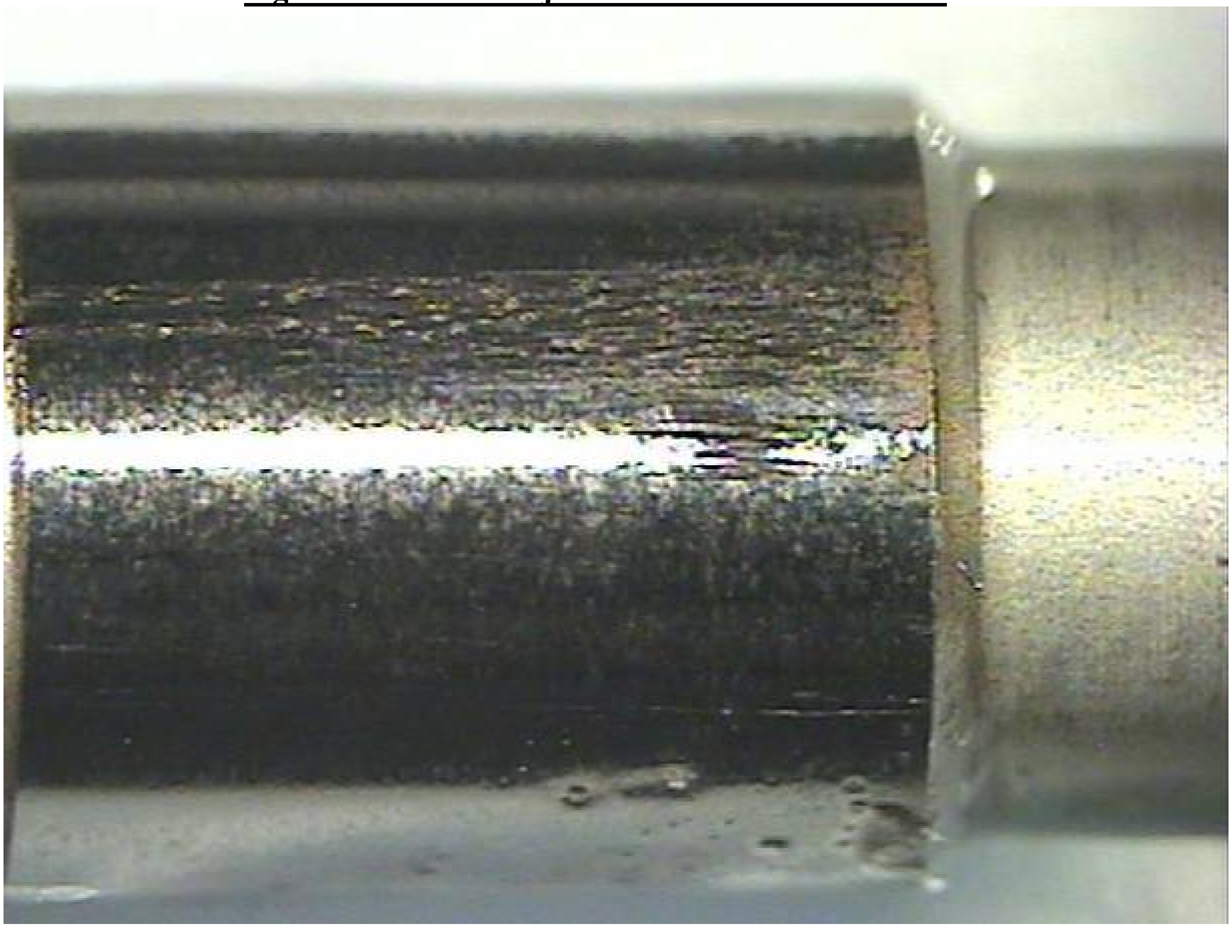
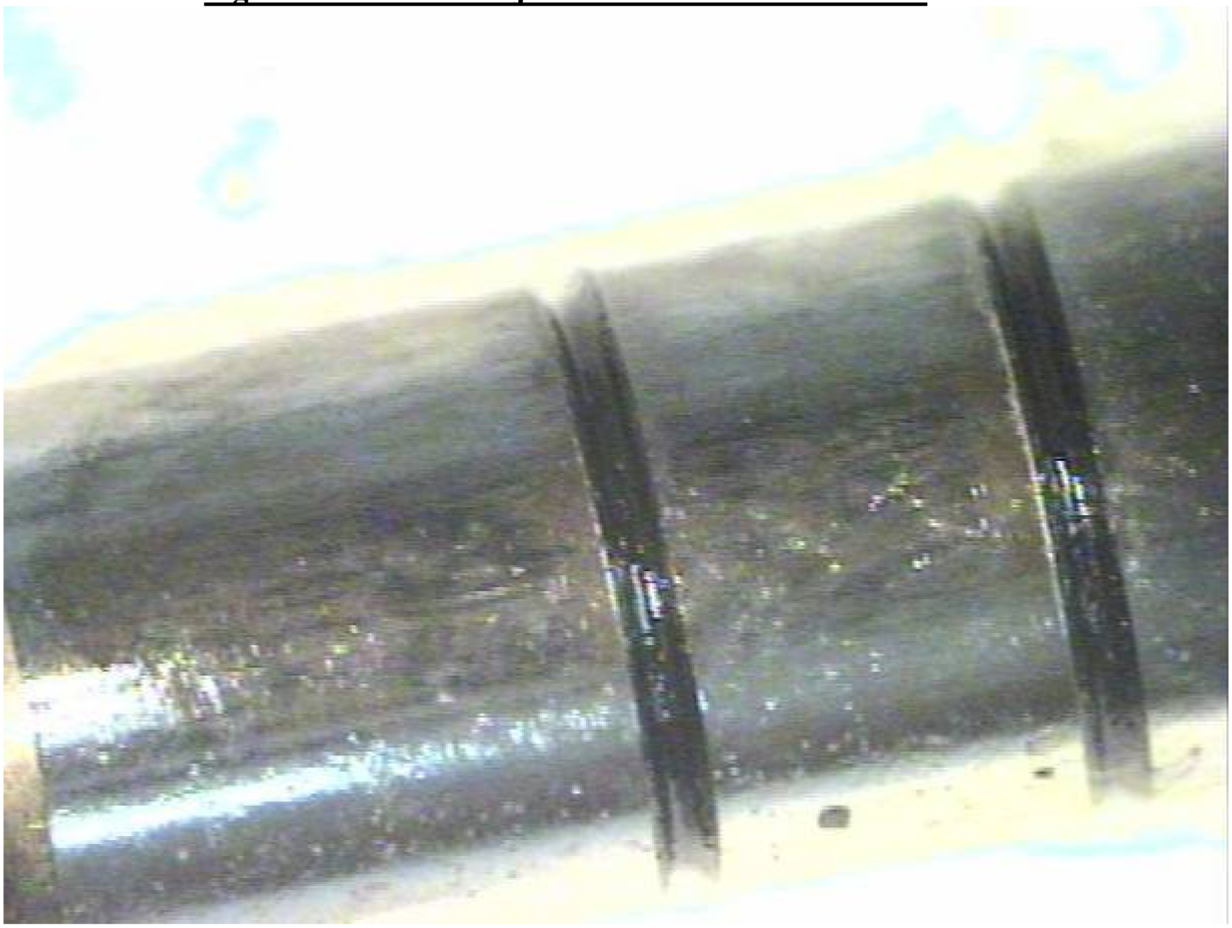


Figure III- 8.1 Liter Injector Command Piston Scuff



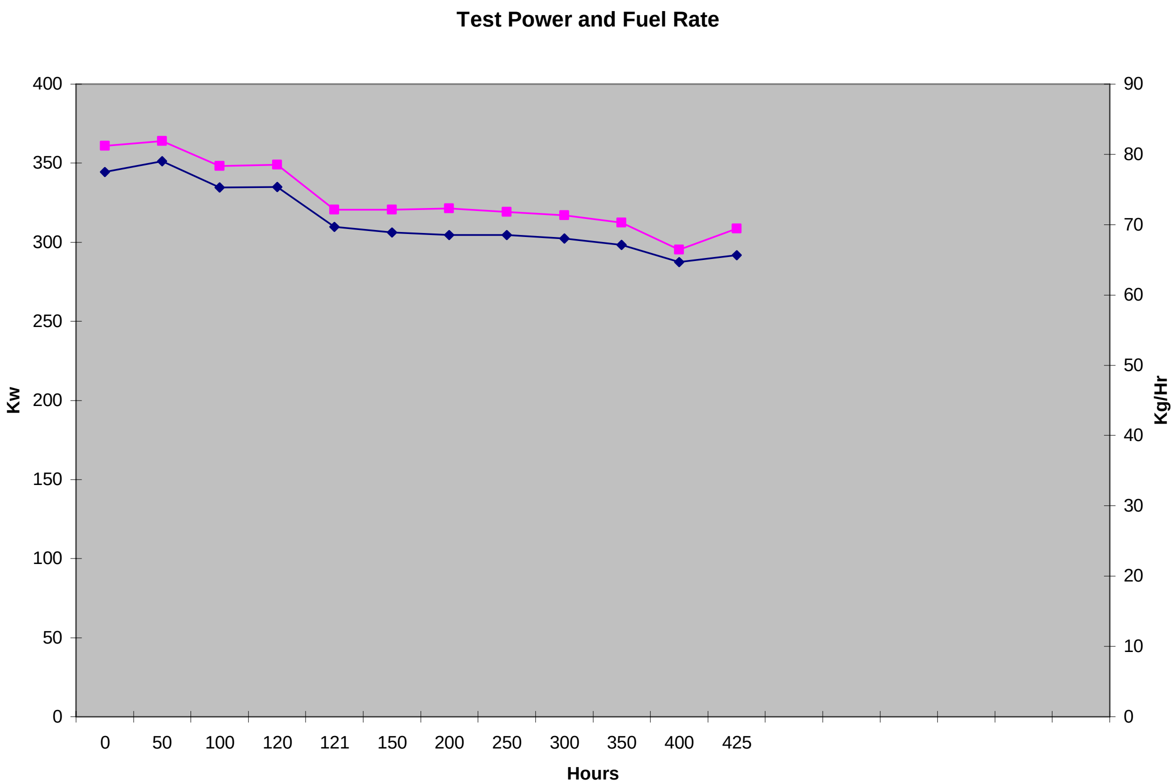
12.5 Liter Engine

Table X - 12.5 Liter Test Power and Fuel Rate – Run #1

12.5Liter Engine Test power and Fuel Rate Run #1 08 June 2004 - 02 August 2004

Hours	HP	Kw	#/HR	Kg/Hr	
0	484	360.9247	170.8	77.47488	
50	488	363.9075	174.2	79.01712	
100	467	348.2476	166	75.2976	
120	468	348.9933	166.1	75.34296	
121	430	320.6562	153.6	69.67296	New fuel Batch
150	430	320.6562	151.9	68.90184	
200	431	321.4019	151	68.4936	
250	428	319.1648	151	68.4936	
300	425	316.9277	150	68.04	
350	419	312.4534	148	67.1328	
400	396	295.302	142.6	64.68336	
425	414	308.7248	144.8	65.68128	

Graph IV- 12.5 Liter Test Power and Fuel Rate – Run #1



Event Listing – 12.5 Liter Engine Run #1

- Start test 08 June 2004
- 8% power loss @ 120 hours
- 10% power loss by 306 hours; diagnosed malfunctioning injectors
- Terminated test 02 August 2004
- observed cavitated internal high pressure injector seals

Figure IV- 12.5 Liter EUI Cavitated Internal Injector Sealing Surface

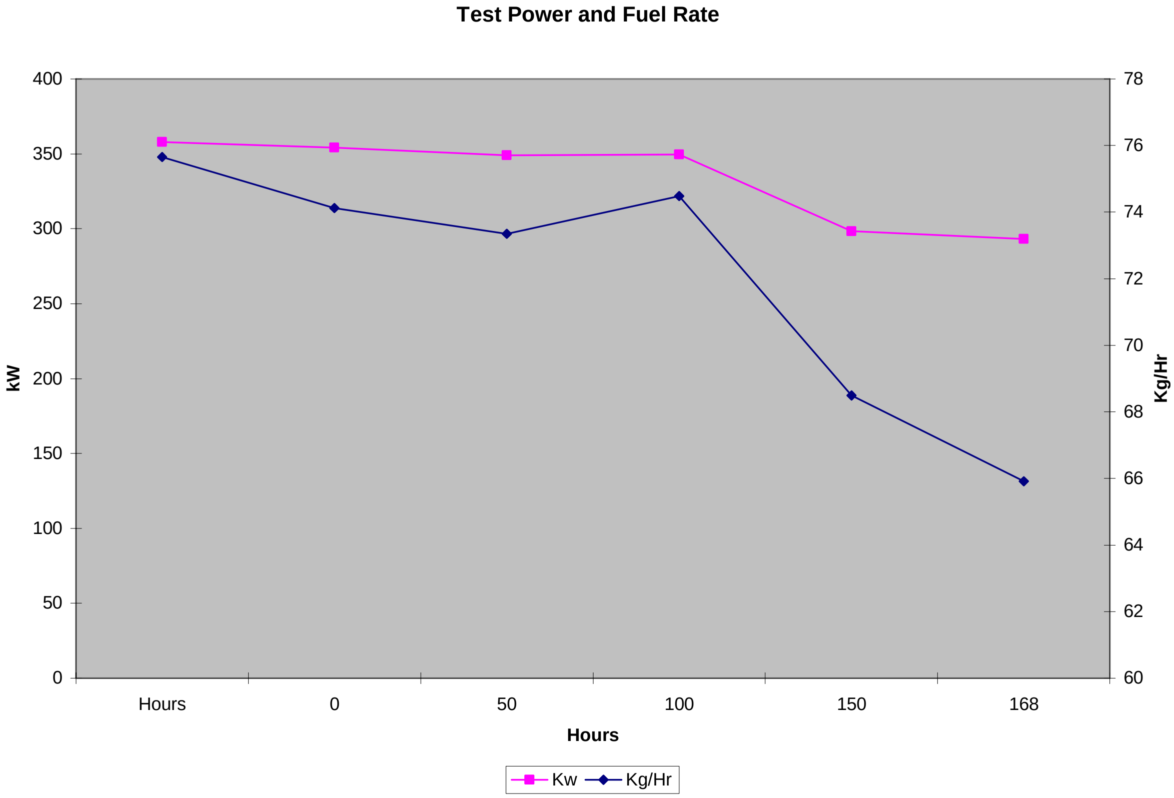
Table XI- 12.5 Liter Test Power and Fuel Rate – Run #2

12.5Liter Engine Test power and Fuel Rate

Run #2 17 February 2006- 06 March 2006

Hours	HP	Kw	#/HR	Kg/Hr
0	480	357.9418	166.8	75.66048
50	475	354.2133	163.4	74.11824
100	468	348.9933	161.7	73.34712
150	469	349.739	164.2	74.48112
168	400	298.2849	151	68.4936
169	393	293.0649	145.3	65.90808

Graph V- 12.5 Liter Test Power and Fuel Rate – Run #2



Event Listing – 12.5 Liter Engine Run #2

- Start Run #2 17 February 2006 with new injectors; increased fuel rail charge pressure; improved fuel cooling
- Power/fuel rate loss; 8-15% 24 February 2006 @ 166 hours
- Same injector cavitation failure mode as Run #1
- Terminated test on 06 March 2006.

Figure V - 12.5 Liter EUI Cavitated Internal Injector Sealing Rings-Run #2

Discussion of Events and Results

8.1 Liter Engine

Successful conclusion and reporting of the regulated and unregulated emissions test comparison for the Tier II non- road John Deere diesel engines preceded the launch of the planned durability test for E diesel fuels. The first engine on test was the 8.1 Liter engine using the newest technology fuel system, the Denso common rail fuel system.
The Full Load, Rated Speed (FLRS) test was chosen due to its simplicity yet aggressive failure mode identification experienced in previous product qualification tests at John Deere.

The E diesel test fuel used in Run 1 of the 8.1Liter engine was blended with Additive A in the concentration recommended by the additive supplier as illustrated in Table III for E diesel with a 10% ethanol concentration. Fuel ethanol with the properties illustrated in Table IV was used in a 10% concentration in a market available low sulfur #2 D diesel fuel with properties as illustrated in Table V columns 2D. This resulted in a fuel blend labeled EM-5046-F whose test properties are also shown in Table V. Very low sulfur levels were apparent as well as very robust lubricity properties as judged by both of the widely accepted industry lubricity bench test standards for diesel fuel. Water content beyond that specified for diesel fuel was also recorded.

During 72 hours of test operation (10 March 2004-12 April 2004) the observed power level deteriorated from the expected 98% of #2D power (considered normal for E10 diesel based on previous emissions testing) to 86% of test start power. Hard starting and misfiring was also reported by the test operators. The usual diagnostic procedures (ECU signal, wiring harness integrity, excess flow valve function and fuel filter plugging) yielded no improvement. Replacing all of the electronically actuated fuel injectors resulted in a return to expected test power. Testing was terminated awaiting failure mode identification.

The suspect injectors were returned to Denso for diagnosis. The injectors were found to be intermittently functional and inspection revealed internal deposits, wear and command piston scuffing (Figure II)

Based on these inspection results and previous experience involving injection system deposits and high concentration of fatty acid lubricity enhancers, a decision was made to switch to Additive C for Run #2 on the 8.1 Liter engine. This fuel blend was designated as EM-5374-F and had the properties listed in Table V. This fuel was used for the remainder of the durability tests.

Run #2 of the 8.1 Liter engine operated between 02 November 2004 and 06 December 2004. Power levels started out at 99% of rated power and gradually deteriorated to 90% of test start by 500 hours. Hard starting was noted at 440 hours and the engine was unable to complete the scheduled 500 hour emissions test. Diagnostics again indicated faulty injectors and they were returned to Denso for in-depth analysis. The inspection results were similar to the injectors from Run #1.
Additional Failure Mode Identification was deemed necessary and further analysis proceeded as follows:

- injectors were sent to the additive suppliers for analysis
- SwRI’s metallurgical department was contracted for further in- depth analysis

A report “Metallurgical Evaluation of Two 6081 E-diesel Injectors” written by Dr. Richard A. Page of SwRI (Appendix I) concluded:

- light to extreme wear possibly accelerated by the wear particles themselves was caused by poor lubrication
- corrosion pitting most likely catalyzed by the chlorine and sulfur element species present in the pits
- black deposits characterized by amorphous and graphitic carbon

Denso’s inspection also confirmed the concern about deposits and wear. One additive supplier’s inspection indicated no concern about the condition of the injector components.
The other additive supplier’s inspection concurred with the SwRI conclusions.

12.5 Liter Engine

The second engine to start E10 diesel durability test was the 12.5 Liter engine with the Delphi Electronic Unit Injector fuel system. The 1st Run started on 08 June 2004 using E diesel fuel EM-5374-F described in Table V. The test procedure, operating conditions and results were as shown in Tables I, II, VIII, IV and Figure IV. A power and fuel rate drop occurred at 120 hours co-incident with a fuel supply renewal. Testing continued at 86% of rated power (expected E10 diesel power was 92% of rated) for several weeks as fuel was analysis was conducted and various other diagnostics were implemented. Further power deterioration caused Run #1 to be terminated on 02 August 2004. The injector micro-cavitation discovered and exhibited in Figure IV can be caused by vapor bubbles in the injector fuel supply. The vapor pressure of the E diesel and temperature and pressure of the fuel supply in the injector can affect the formation of these vapor bubbles during the injection cycle. Documentation of existing pressure and temperature conditions during the durability test when the cavitation occurred was desired. A short term test plan to document the pressures and temperatures of the fuel supply and explore ability to change these conditions was established.
Initial measurements indicated vapor bubbles in the fuel supply were causing power instability. Additional fuel cooling stabilized power and fuel rail charge pressure was increased from 620 kPa (90 psi) to 827 kPa (120 psi).
Run #2 of the 12.5 Liter engine was started on 17 February 2006 with the fuel cooling maximized and the fuel rail pressure increased to 827 kPa. 166 hours into the test sudden fuel rate and power drop indicated that internal cavitation may once again be a problem. Subsequent inspection of the injectors confirmed that all six internal sealing washers suffered cavitation damage (Figure V). The test was terminated. A listing of potential future work research on this fuel system could include:

- redesigned Delphi fuel injector (although no retrofit for the tested injector is planned)
- isolated fuel supply rail could allow more effective fuel supply cooling
- fuel supply re-routing could allow much higher charging pressures

6.8 Liter Engine

The 6.8 Liter engine was the last test engine to start E10 diesel testing on 13 July 2005 using E10 diesel fuel EM-5374-F described in Table V. The test procedure, operating conditions and results were as shown in Tables I, II, VIII, IV and Figure IV. 97 hours into the test program a power loss was caused by an injector tip failure (injector #5) (Figure I). The injector was replaced and testing continued while diagnosis of the failed injector proceeded. A second injector tip (injector #4) failed at 177 test hours. All six injectors were replaced and testing continued uneventfully to 500 hours. An emissions test was conducted and the engine resumed testing uneventfully for another 500 hours at which time the emissions test was repeated. The results of the "0" hour baseline, 500 emissions test and 1000 hour emissions tests are shown in Table V. Some directional increasing levels of particulates and smoke were noted but all regulated emissions data met the Tier II requirements.

Diagnostics of power loss and hard starting at 1326 hours eventually required that the injection pump be removed from the engine. A decision was made to terminate the test on 09 February 2006.

All injectors, fuel injection pump and fuel samples were returned to Stanadyne for failure mode analysis. Stanadyne's fuel lubricity analysis concurred with continuing analysis's performed at SwRI showing very strong lubricity properties (Table V).

Injector analysis indicated reduced opening pressure as observed on the previous batch of tip failure injectors. Wear between the injector valve and seat is a common cause of loss of opening pressure.

Performance on the injection pump test stand pin-pointed the problem as the fuel control solenoid. The Epoxy potting material apparently caused distortion affecting the solenoid's ability to accurately control fuel rate. Replacement of the failed solenoid resulted in expected, specified test stand results. Ryton solenoid potting material was substituted as a running change in 2004 to upgrade durability performance in various aggressive fuel environments.

Conclusions and Recommendations

- The internal power components of all three engines exhibited normally expected wear condition during inspection at termination of the test program.

- The Stanadyne DE-10 rotary distributor fuel injection pump exhibited normal wear patterns compared to operation on #2 diesel fuel indicating acceptable lubricity.

- The Epoxy potting material of the fuel control solenoid was found to be incompatible with the E diesel environment over extended operation. The Ryton potting material now specified needs compatibility tests in E diesel.

- The Stanadyne RSN pencil injector exhibited excessive injector valve seat wear operating on E10 diesel fuel that demonstrated robust lubricity properties on industry specified lab bench tests. New lubricity bench tests may need to be developed for E diesel or present bench tests may need to be revised.

- The electronic fuel injectors in the Denso common rail fuel system malfunctioned due to wear, corrosive pitting and deposits in and on the injector command piston, valve and body. Lubricity robustness, additive stability in a high water environment and excessive use of fatty acid lubricity enhancements have caused these symptoms in injection systems in the past.

- The Delphi electronic unit injectors (EUI) used in the 12.5 Liter engine failed due to cavitation erosion of the high pressure internal sealing washers. The higher vapor pressure property of E diesel is the apparent direct cause of this observed weakness. Fuel cooling effectiveness is limited by the routing of the fuel supply through the cylinder head. Testing at fuel supply pressures in the 200 psi region remains to be explored. Redesigned injectors, an external fuel supply rail design allowing higher charging pressures yet and uses of more effective fuel cooling are features that could provide improved injector life.

Appendix

Metallurgical Evaluation of Two 6081 E-Diesel Injectors

By
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Final Report
SwRI→ Project No. 03.06811.02.001

Submitted to
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Falls, IA 50613

February 2006

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1.0 INTRODUCTION

Two 6081 e-diesel injectors were submitted for evaluation. The two injectors were identified as “Run 1, Injector 1” and “Run 2, Injector 5”. The two injectors had reportedly been involved in engine tests utilizing a 10% ethanol e-diesel fuel. The two injectors reportedly differed in the fuel additive used and the time operated on the 10% ethanol e-diesel, however, the specifics of the differences were not provided. Previous examinations performed in other laboratories had reportedly identified the sliding surfaces between the injector needle and the bore of the injector body as the problem areas. Hence, the evaluations performed in this study were limited to those needle/bore sliding surfaces. The results of those evaluations are described below.

2.0 STEREOMICROSCOPE EXAMINATIONS

Run 1, Injector 1 Needle Surfaces

An overall view of the sliding surfaces on the needle from run 1, injector 1 is provided in Figure 1(a). The surfaces appeared to be in good condition with no apparent evidence of galling. Examination at higher magnifications identified the presence of some small longitudinal score marks, as shown Figures 2(a) and 3(a). The surfaces appeared to be relatively free of surface deposits. Furthermore, no evidence of environmental attack was observed.

Run 2, Injector 5 Needle Surfaces

An overall view of the sliding surfaces on the needle from run 2, injector 5 is provided in Figure 1(b). A narrow band along the upper end of the needle, far right in Figure 1(b), appeared to be free of any wear damage. The remainder of the surface was dulled from wear damage. Examination at higher magnifications identified extensive longitudinal scoring, as shown in Figures 2(b) and 3(b). The scoring was the deepest and most extensive along the upper surfaces.

Run 1, Injector 1 Bore Surfaces

The injector body was longitudinally sectioned using a wire EDM. The two halves of the sectioned body from run 1, injector 1 are shown in Figure 4(a). The wear surfaces, located on the left side of the photograph, were quite smooth and free of any significant deposits. The original honing marks were the prominent feature observed during higher magnification examinations, as shown in Figure 5. Some light longitudinal scoring was also apparent. Portions of the bore exhibited a lightly etched appearance, as shown in Figure 7(a).

Run 2, Injector 5 Bore Surfaces

The injector body was longitudinally sectioned using a wire EDM. The two halves of the sectioned body from run 2, injector 5 are shown in Figure 4(b). The wear surfaces are located on the left side of the photograph. Three dark circumferential bands, apparently corresponding to the three grooves on the needle surface, were apparent. Significant differences between the two sectioned halves were apparent at higher magnification. One side, shown in Figure 6(a), exhibited deep longitudinal grooving to such an extent that all of the original honing marks had been removed. On the opposite side, shown in Figure 6(b), honing marks were still visible and only a small amount of longitudinal grooving was present. Areas that appeared to be shallow corrosion pits filled with corrosion product were also evident on the low wear side of the bore, as shown in Figures 6(b) and 7(b).

3.0 METALLOGRAPHIC EXAMINATIONS

It was originally planned to prepare metallographic cross-sections to evaluate the thickness of surface deposits and the depth and extent of any corrosive attack. However, the absence of deposits of any significant thickness on the wear surfaces and the absence of any uniform corrosive attack made metallographic cross-sections an unsuitable method to obtain useful information about the condition of the wear surfaces. A detailed examination of the surfaces using scanning electron microscopy and energy dispersive xray spectroscopy was considered to be a more suitable approach for these components. The results of the SEM evaluations are presented below.

4.0 SCANNING ELECTRON MICROSCOPE EXAMINATIONS

Run 1, Injector 1 Needle Surfaces

Examination of the needle surfaces of run 1, injector 1 revealed fairly smooth surfaces that exhibited minimal wear. Extensive scoring was not evident, as shown in Figure 8(a), and the original machining marks were still visible on the surface, as shown in Figure 9(a). Second phase particles were evident, however, no evidence of particle pull-out was observed.

Run 2, Injector 5 Needle Surfaces

Examination of the needle surfaces of run 2, injector 5 revealed substantial longitudinal scoring, as shown in Figure 8(b). When viewed at higher magnification, Figure 9(b), second phase particles were evident along with dark, longitudinal streaks. Additionally, sufficient wear had taken place to remove all of the original machining marks from the surface.

Examination of the second phase particles using energy dispersive x-ray spectroscopy (EDS) indicated that they were enriched in W, as shown in Figure 10. The matrix between the particles was iron based with small amounts of Cr, V, W and Mn, as shown in Figure 11. EDS measurements performed within the dark streaks, Figure 12, did not reveal any species besides those from the base alloy. For comparison, an EDS spectrum from an unworn area at the top of the needle, Figure 13, was also obtained. No significant differences were observed between this spectrum and those taken in the worn areas.

Run 1, Injector 1 Bore Surfaces

A cross-hatched pattern from honing was the predominant feature observed on the run 1, injector 1 bore surfaces in the SEM, as shown in Figures 14(a) and 15(a). Scattered, shallow score marks were also present. The surface regions that appeared to be lightly etched in the stereomicroscope exhibited a lightly textured appearance between the honing marks, Figure 16(a), compared to the smooth appearance between the honing marks observed outside of the etched regions, Figure 16(b).

Run 2, Injector 5 Bore Surfaces

One side of the run 2, injector 5 bore exhibited extensive wear with the wear patterns corresponding to the geometry of the mating needle surfaces, as shown in Figure 14(b). The wear patterns were in the form of longitudinal grooving. When viewed at higher magnification, Figure 15(b), the wear surface had the appearance of third body abrasive wear with very fine particulates populating the surface. The opposite side of the bore exhibited only minimal wear as indicated by the presence of the original honing marks, as shown in Figure 17. Shallow, scattered score marks were present along with areas of deposit filled corrosion pits. Comparison of EDS spectra obtained from a clean area on the bore surface, Figure 18, and from within a pit, Figure 19, indicates that the deposits within the pits were iron oxides which contained minor amounts of P, S, Cl, K, Ca, Cu and Zn. The regions of dark deposits that surrounded the pits were found to contain C, P, S, Ca and Zn, as shown in Figure 20.

5.0 RAMAN SPECTROSCOPY

The noncontacting areas of run 2, injector 5 were coated with a continuous black deposit. Similar deposits were not observed on run 1, injector 1. Samples of the black deposit on run 2, injector 5 were solvent extracted and analyzed with Raman spectroscopy. The Raman spectrum obtained from the deposit is shown in Figure 21. The two primary peaks in the spectrum are from sp3 and sp2 carbon, indicating that the black deposit was a mixture of amorphous, diamond-like carbon and graphitic carbon.

6.0 CONCLUSIONS

The following conclusions have been drawn based on the results obtained in this study. 1. The run 1, injector 1 needle and bore appeared to be in relatively good shape. Minimal wear was present as evidenced by the prominence of original machining marks on both surfaces.

2. Light wear damage, in the form scattered, shallow longitudinal score marks, was present on the needle and bore surfaces of run 1, injector 1. Localized regions of very light etching were also present on the bore surfaces.

3. The run 2, injector 5 needle and bore surfaces exhibited extensive wear damage. Wear damage was present in the form of deep longitudinal grooves. The grooves appeared to be the result of third body abrasive wear, possibly from tungsten particles removed from the needle surfaces during wear.

4. Heavy wear was localized on one side of the run 2, injector 5 bore. The opposite side of the bore, which exhibited minimal wear, contained numerous, shallow corrosion pits. Corrosion deposits within the pits contained Cl and S, which would be considered aggressive species.

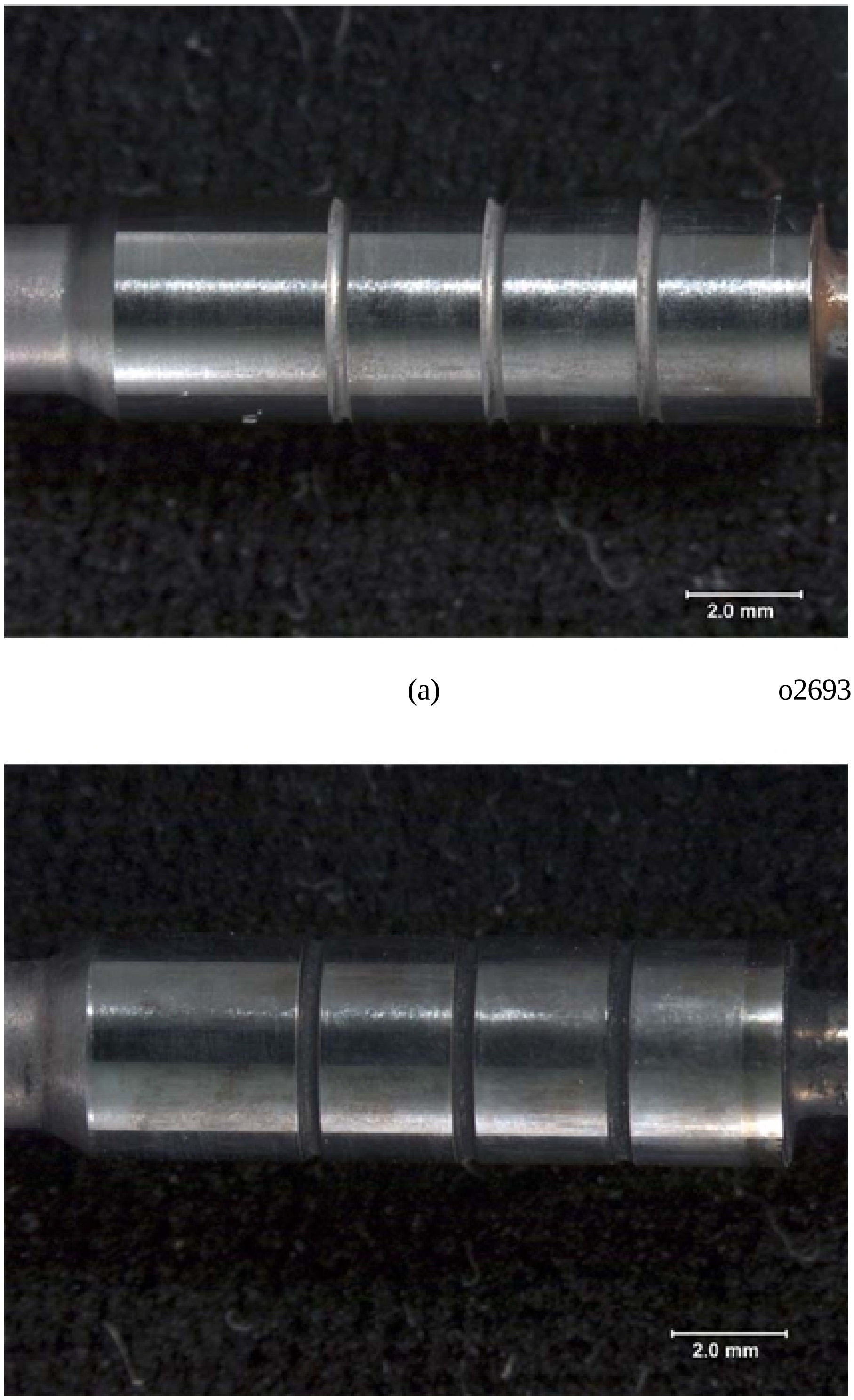
5. The noncontacting surfaces of run 2, injector 5 were covered with a black deposit. The deposit was identified as amorphous and graphitic carbon by Raman spectroscopy.

6. Both injectors exhibited evidence of corrosive attack of the bore surface. The attack on run 1, injector 1 was in the form of a very light etching and did not appear to affect the performance of the injector. The attack on run 2, injector 5 was in the form of scattered pitting and was clearly sufficient to degrade injector operation. Sulfur and chlorine species in the fuel appeared to be responsible for the pitting.

7. Although black deposits were present on noncontacting surfaces, the heavy wear observed on run 2, injector 5 did not appear to be the result of these deposits. Rather, the wear was likely influenced by poor lubrication of the sliding surfaces and/or the pitting of the bore surface.

8. The combination of heavy wear and pitting observed on run 2, injector 5 was the likely cause of the performance drop observed on this injector.

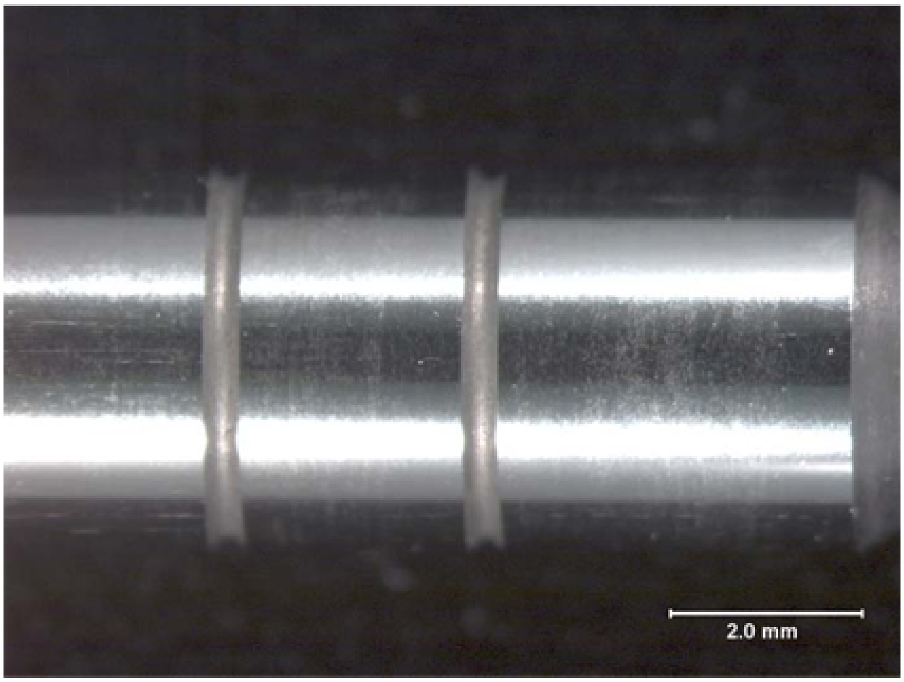
9. The sliding surfaces on run 1, injector 1 exhibited only minor wear and corrosion damage and no significant surface deposits were observed. The condition present in this injector would not be expected to degrade its performance.



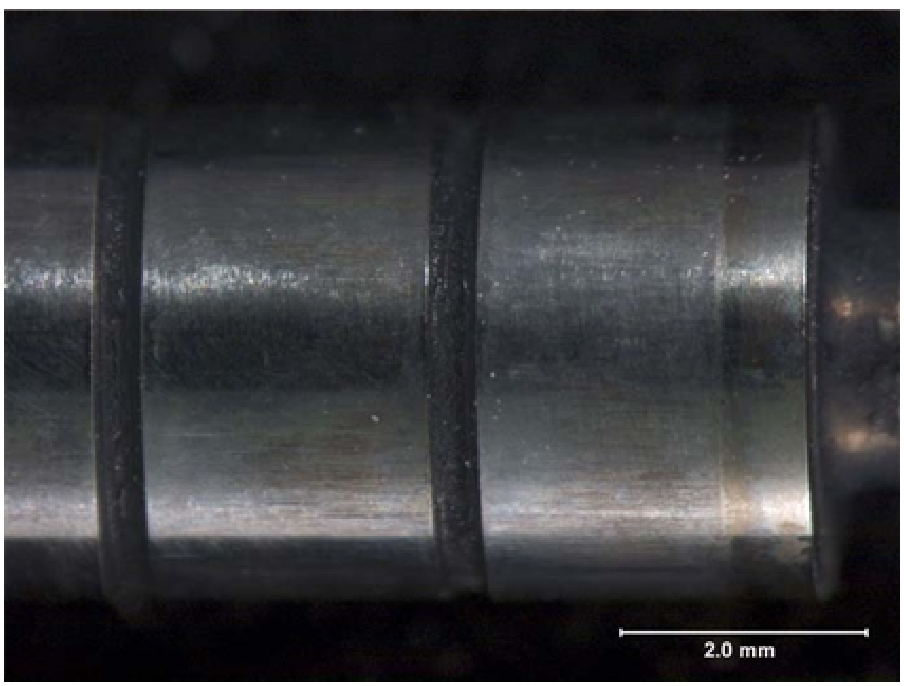
(a) o2693

(b) o2690

Figure 1. Overall views of the sliding surfaces on the needles from (a) run 1, injector 1 and (b) run 2, injector 5.

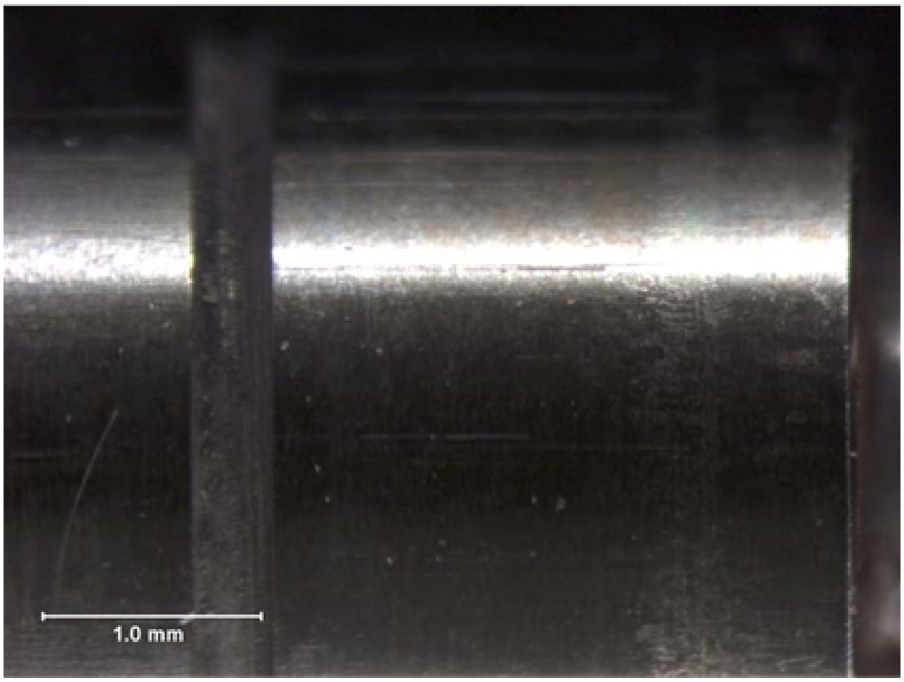


(a) o2720

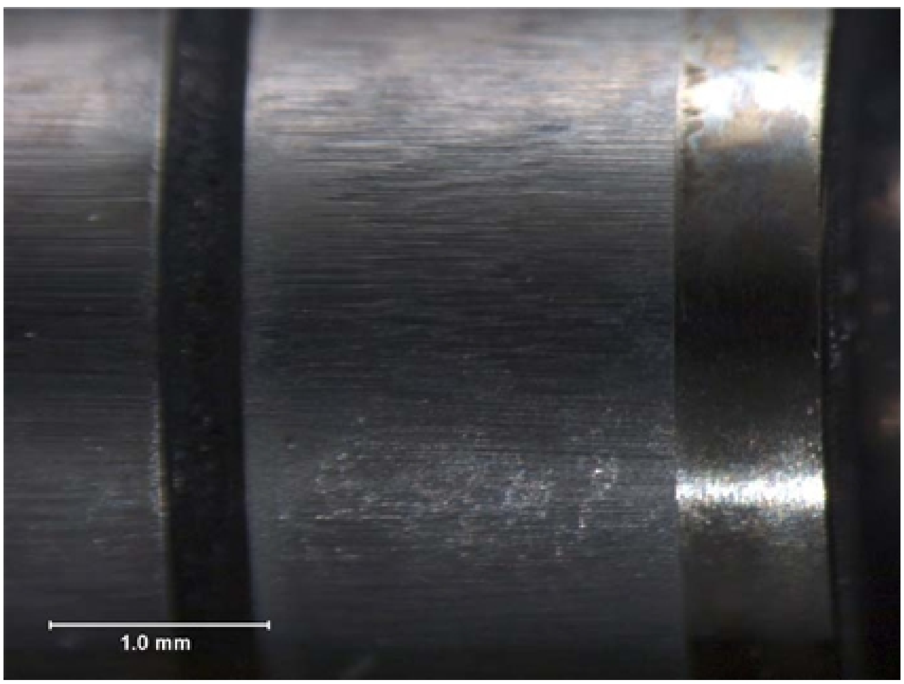


(b) o2691

Figure 2. Intermediate magnification stereomicroscope images of the upper end of the sliding surfaces on the needles from (a) run 1, injector 1 and (b) run 2, injector 5.

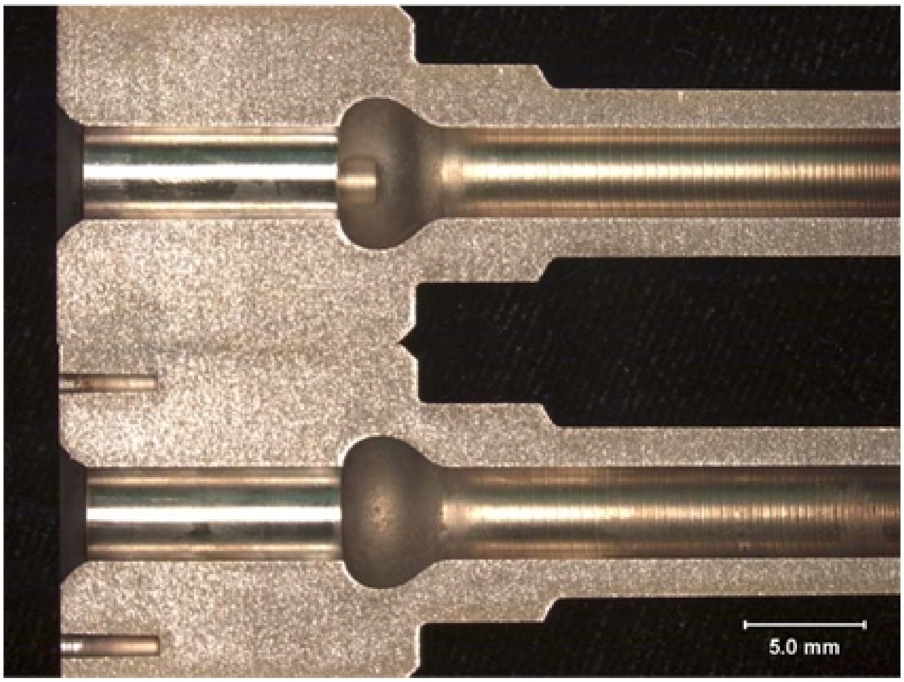


(a) o2693

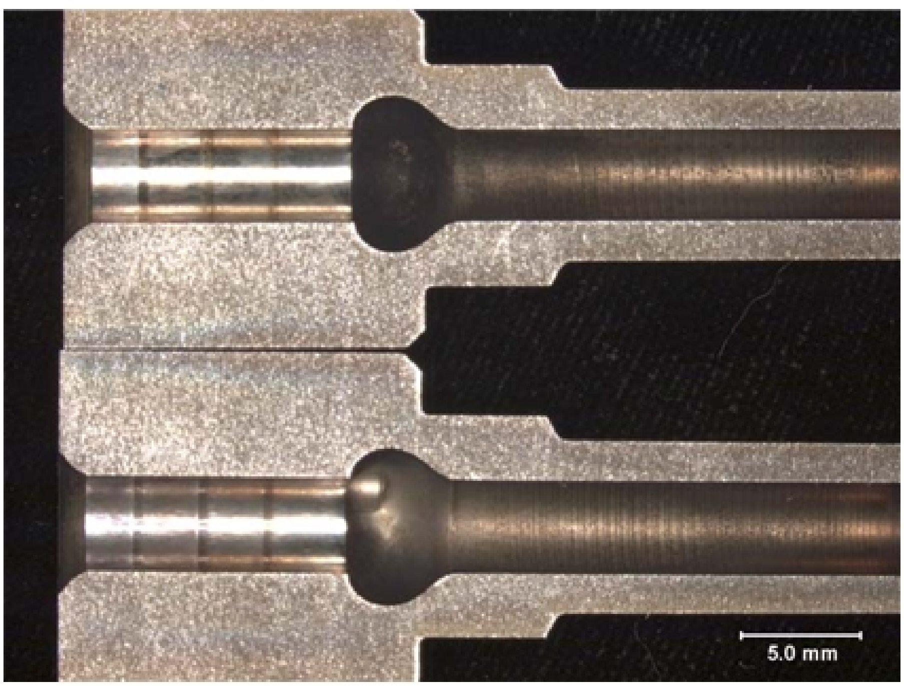


(b) o2690

Figure 3. High magnification stereomicroscope images of the upper end of the sliding surfaces on the needles from (a) run 1, injector 1 and (b) run 2, injector 5.

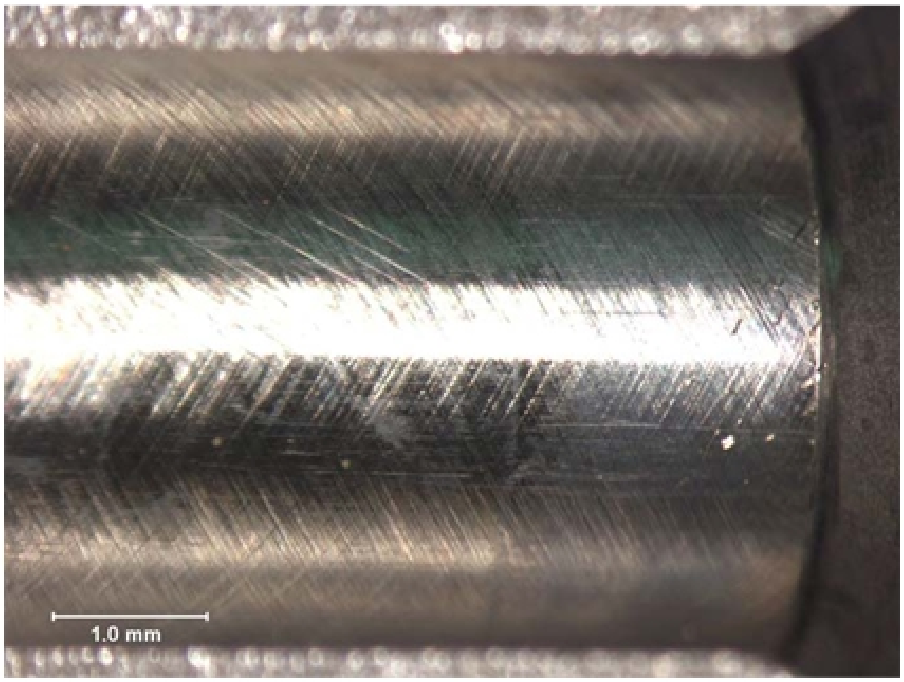


(a) o2715

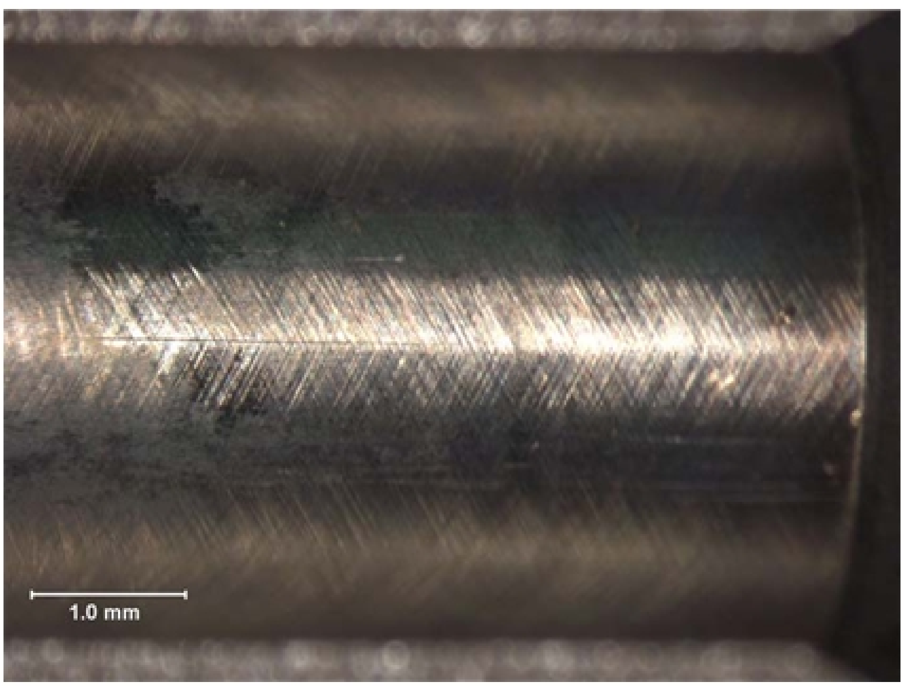


(b) o2717

Figure 4. Overall views of the inside surfaces of the sectioned injector bodies from (a) run 1, injector 1 and (b) run 2, injector 5.

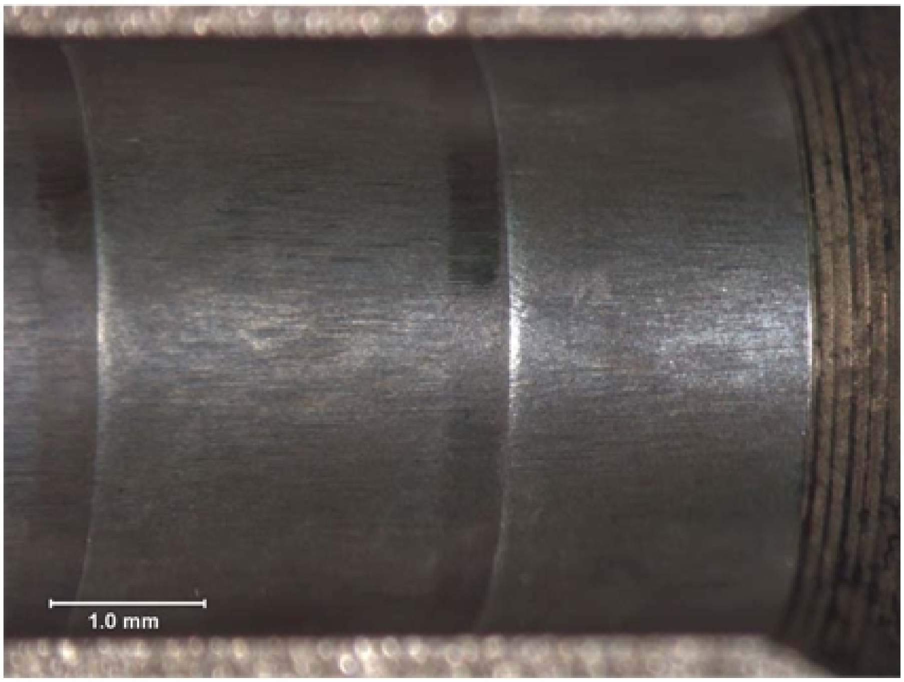


(a) o2740

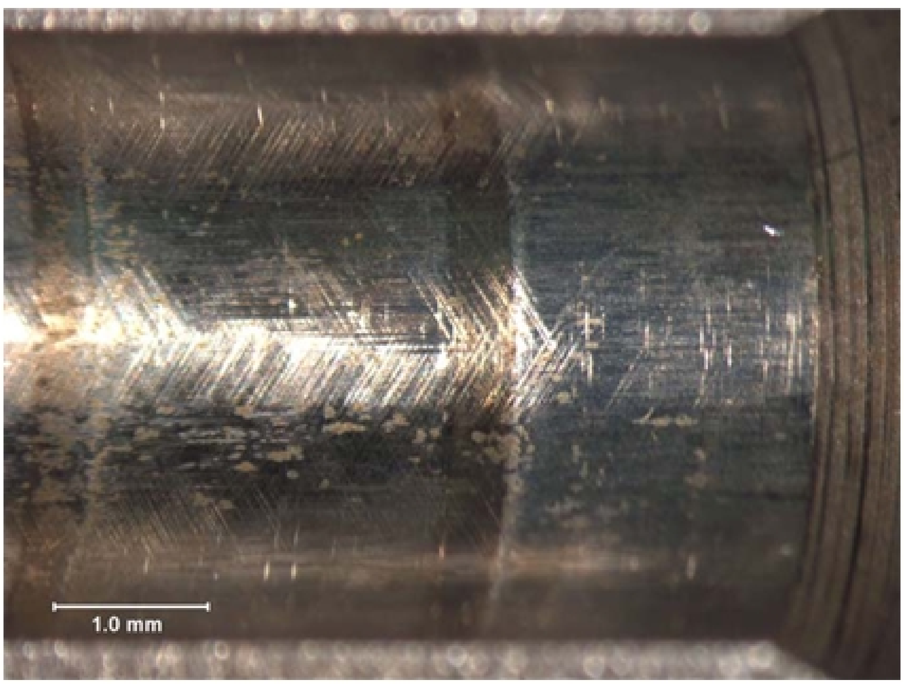


(b) o2741

Figure 5. Higher magnification stereomicroscope images of opposite sides of the inside surface of the injector body from run 1, injector 1.

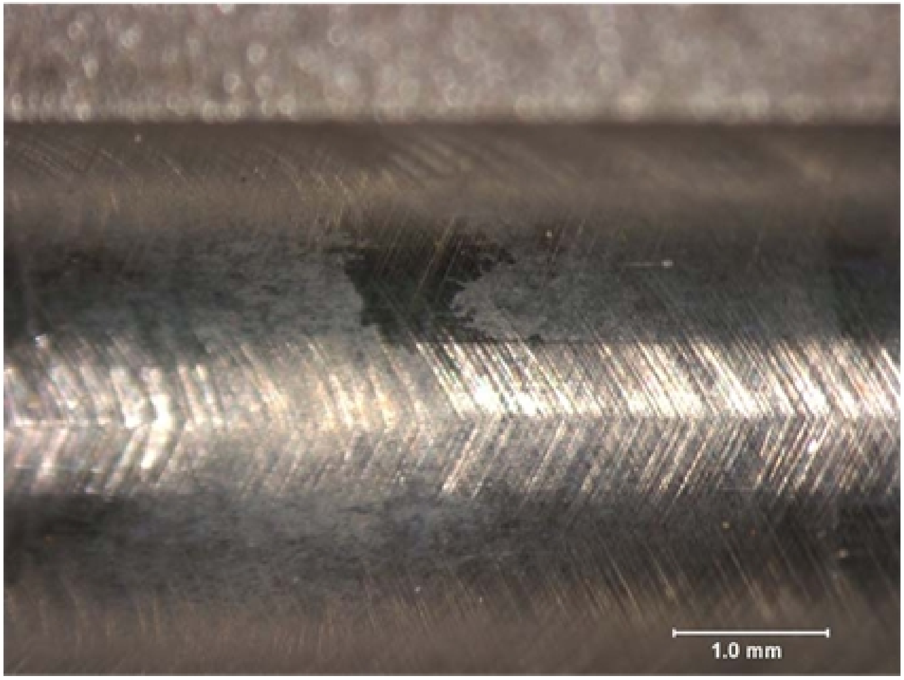


(a) o2738

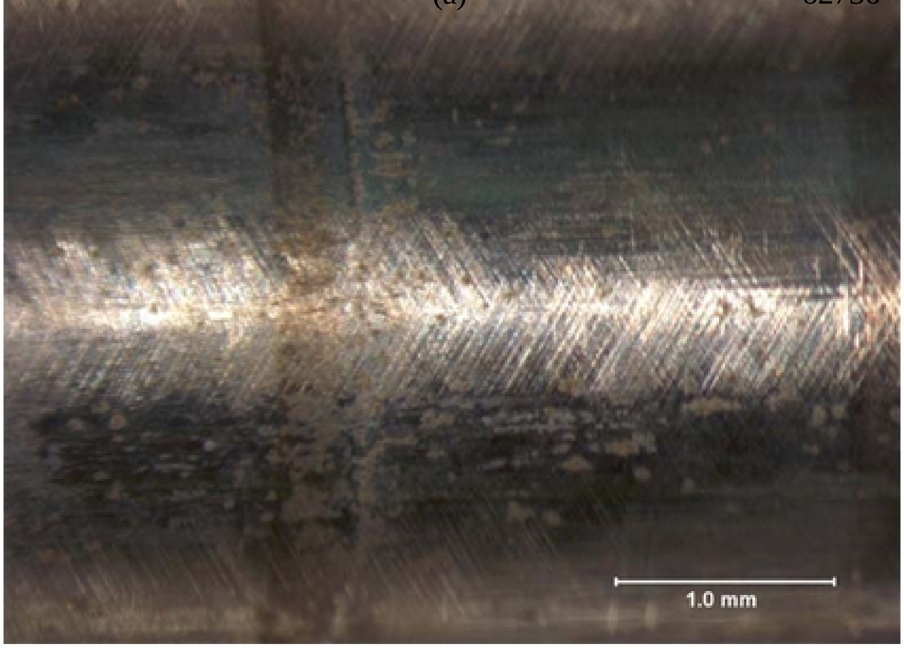


(b) o2739

Figure 6. Higher magnification stereomicroscope images of opposite sides of the inside surface of the injector body from run 2, injector 5.



(a) o2736



(b) o2737

Figure 7. Stereomicroscope images of (a) apparent etching and (b) pitting on the inside surfaces of the injector bodies from run 1, injector 1 and run 2,

injector 5, respectively.

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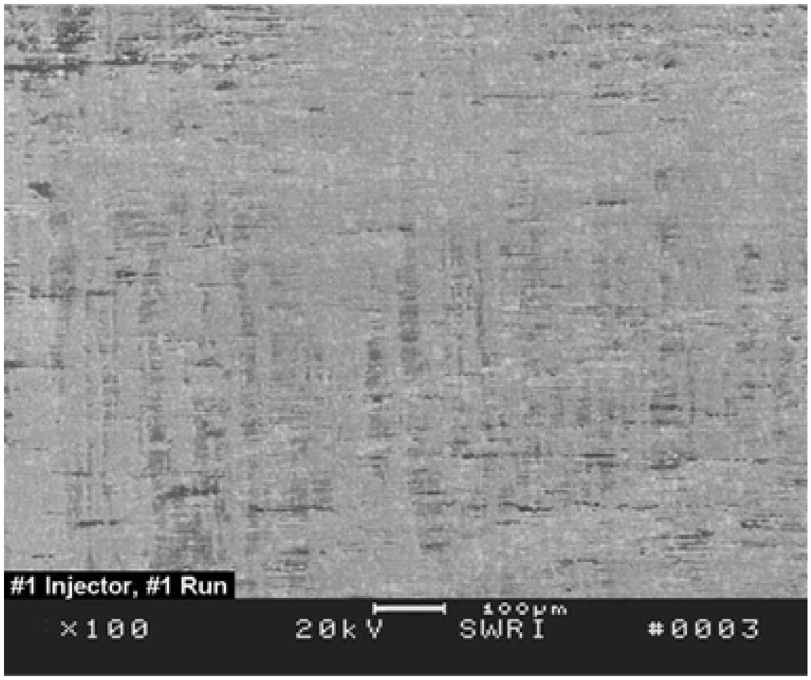
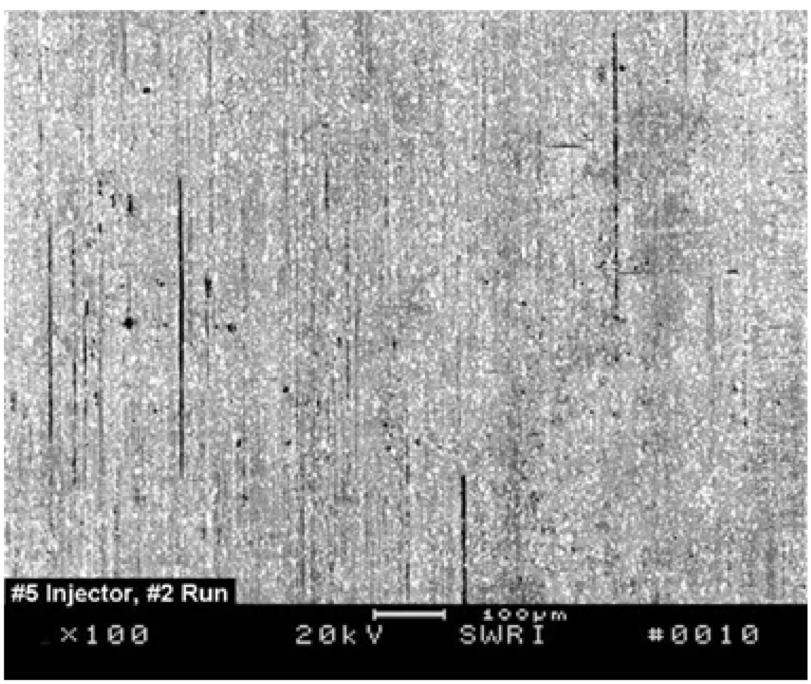
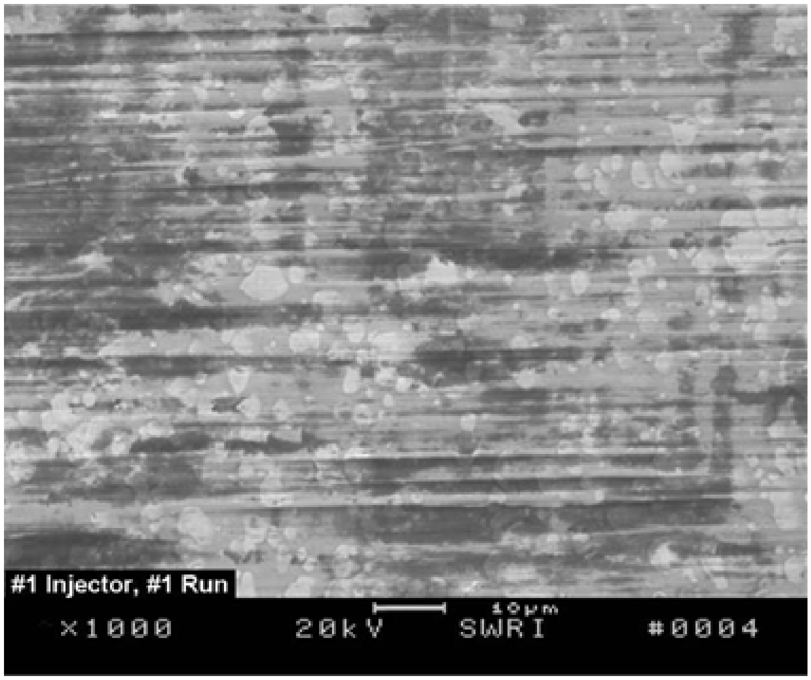


(a) s0679

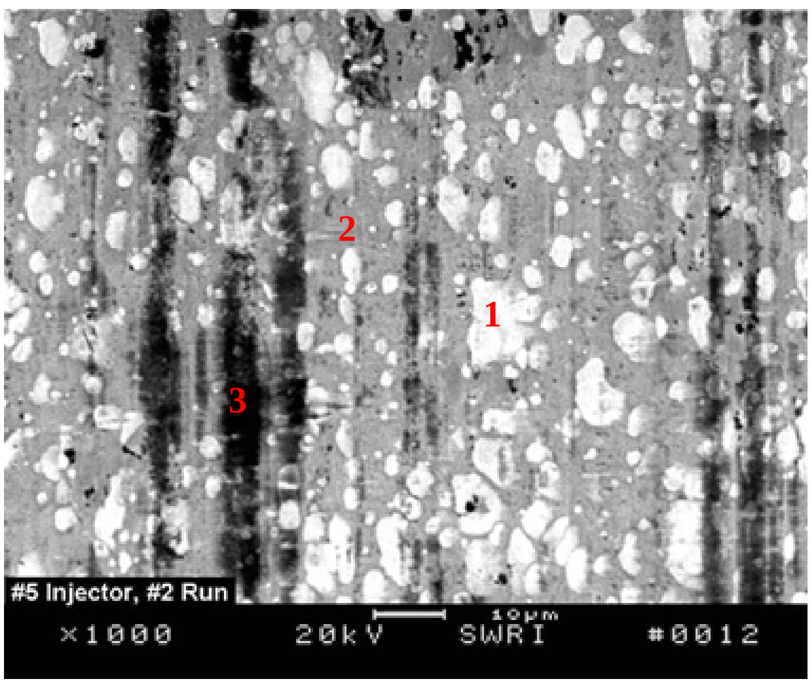


(b) s0683

Figure 8. Scanning electron microscope images of the sliding surfaces on the needles from (a) run 1, injector 1 and (b) run 2, injector 5. The sliding direction is vertical.



(a) s0680



(b) s0684

Figure 9. High magnification scanning electron microscope images of the sliding surfaces on the needles from (a) run 1, injector 1 and (b) run 2, injector 5. The sliding direction is vertical.

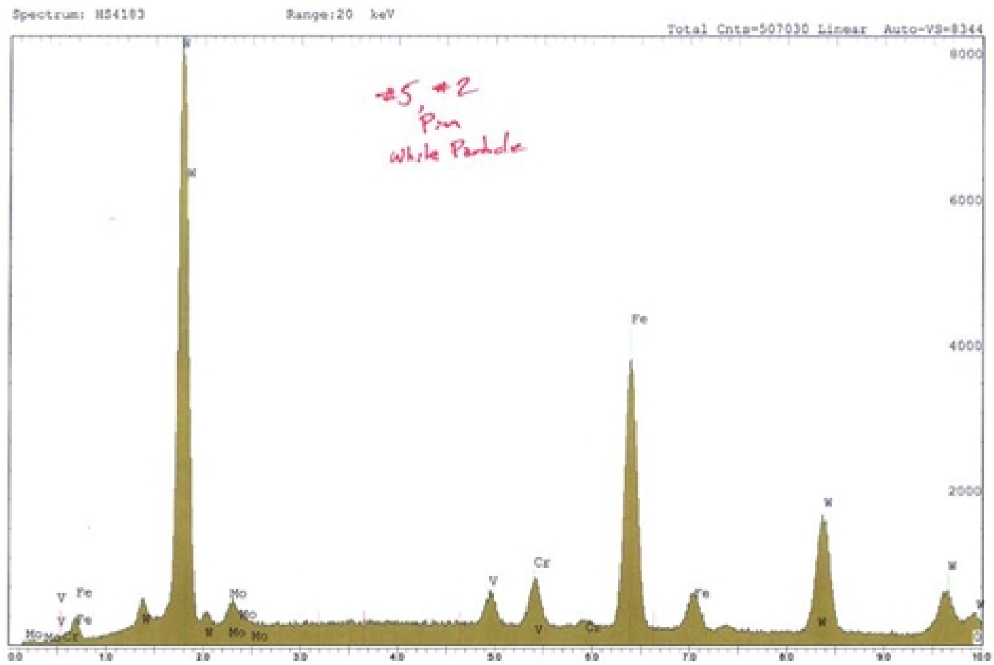


Figure 10. EDS spectrum from location 1 in Figure 9(b).

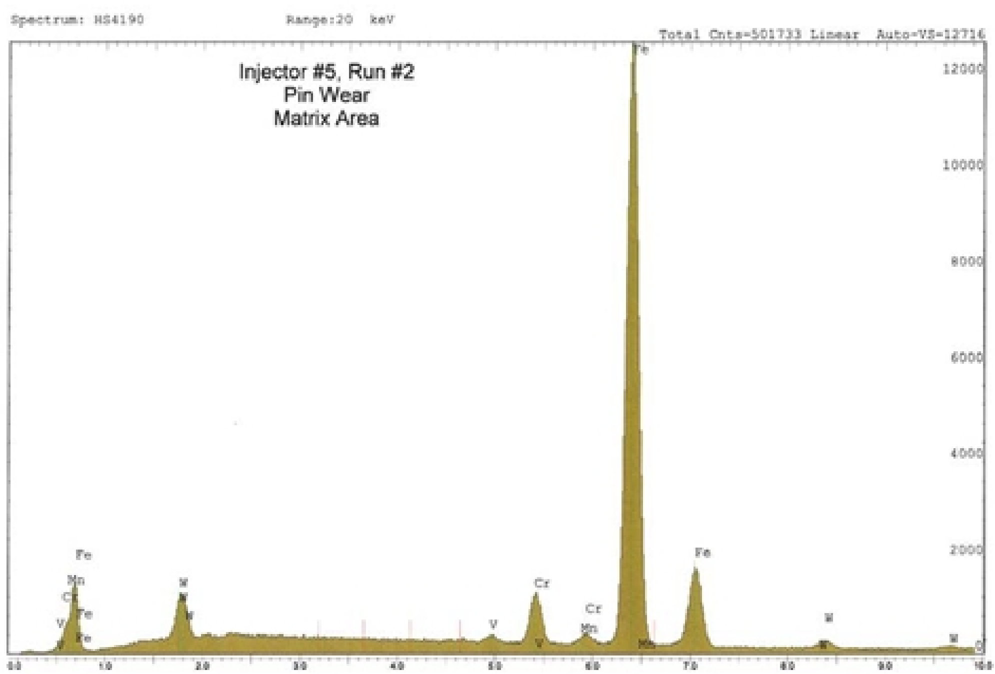


Figure 11. EDS spectrum from location 2 in Figure 9(b).

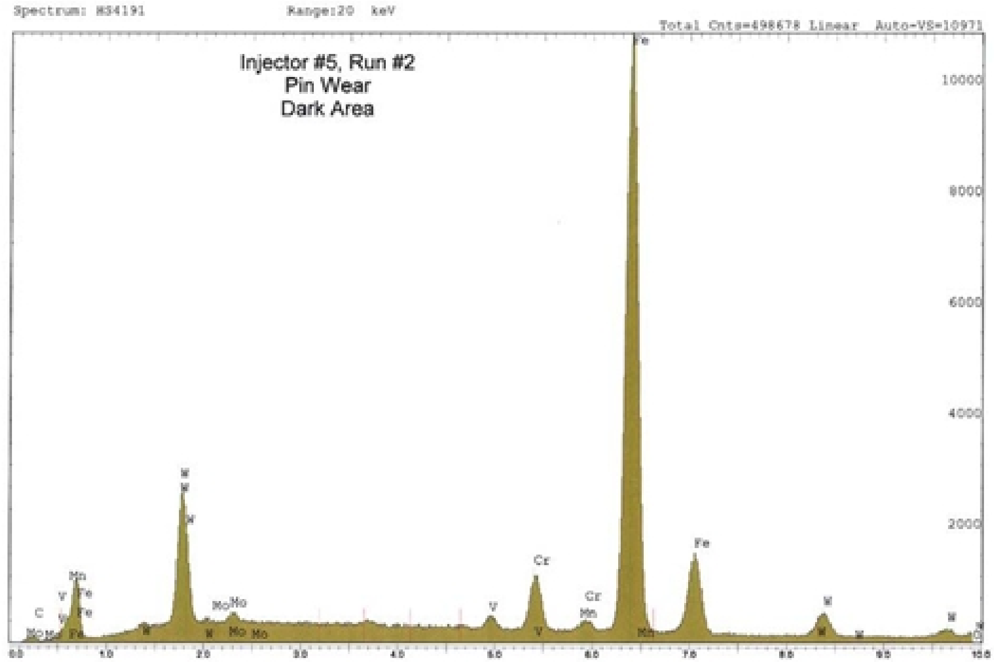


Figure 12. EDS spectrum from location 3 in Figure 9(b).

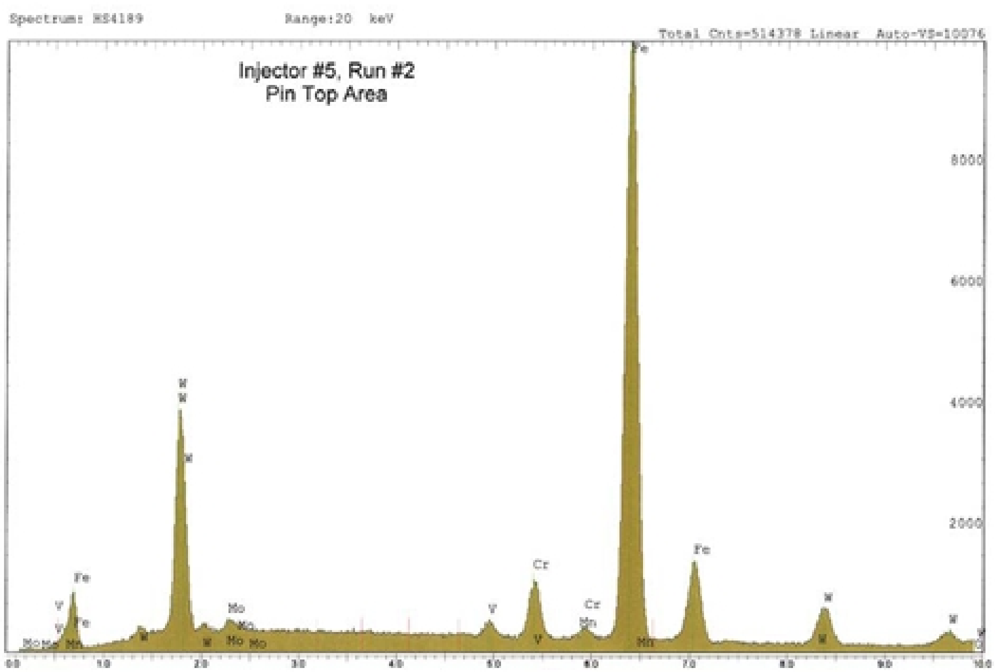
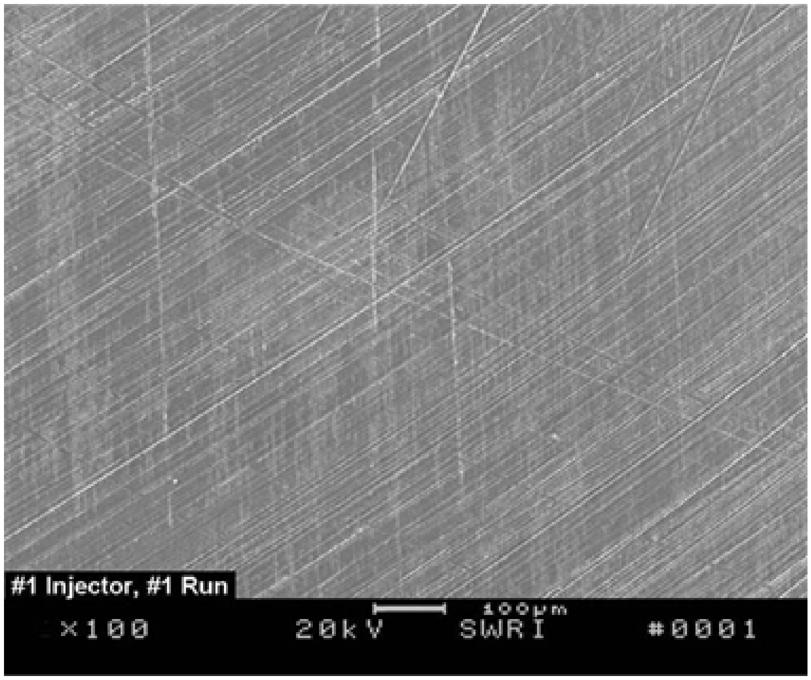
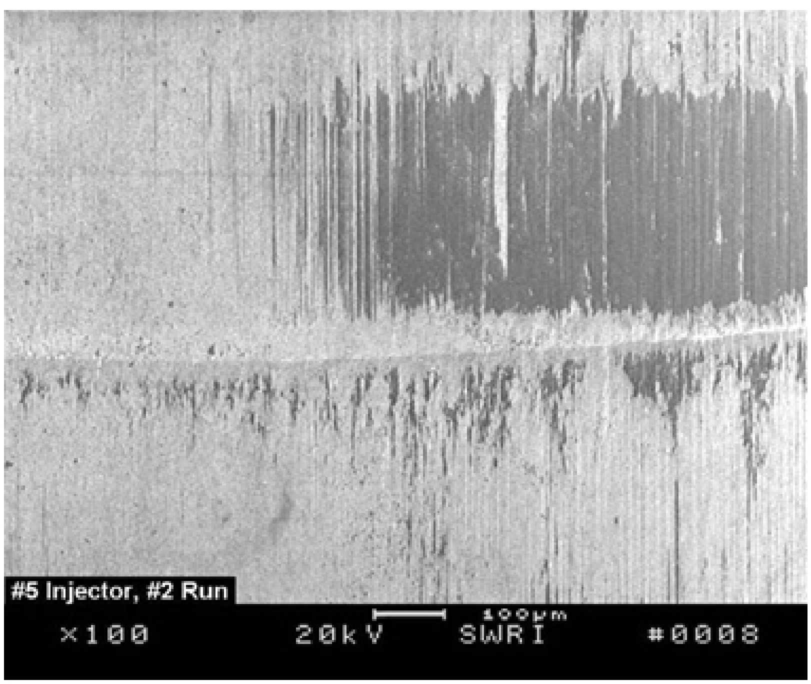


Figure 13. EDS spectrum from above the worn area on the needle from run 2, injector 5.

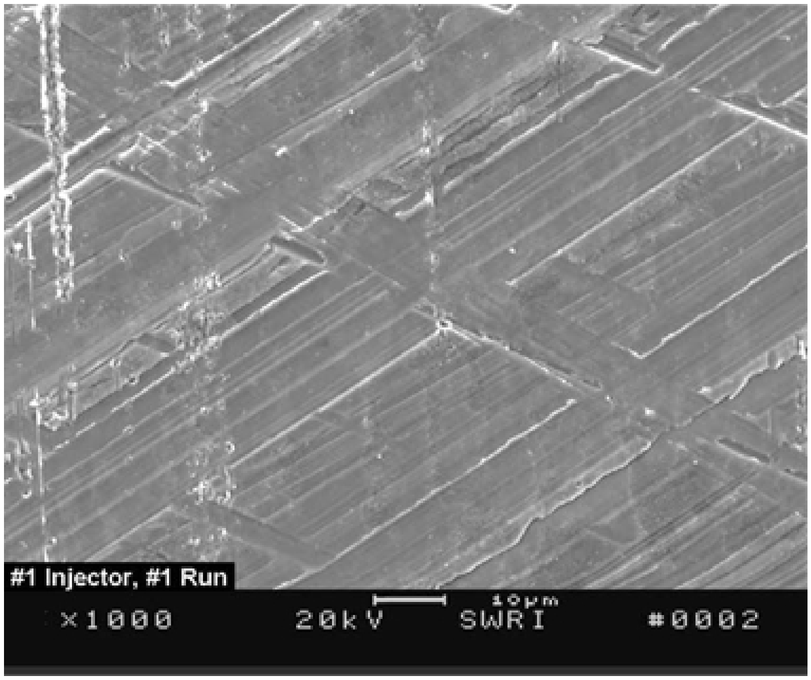


(a) s0677

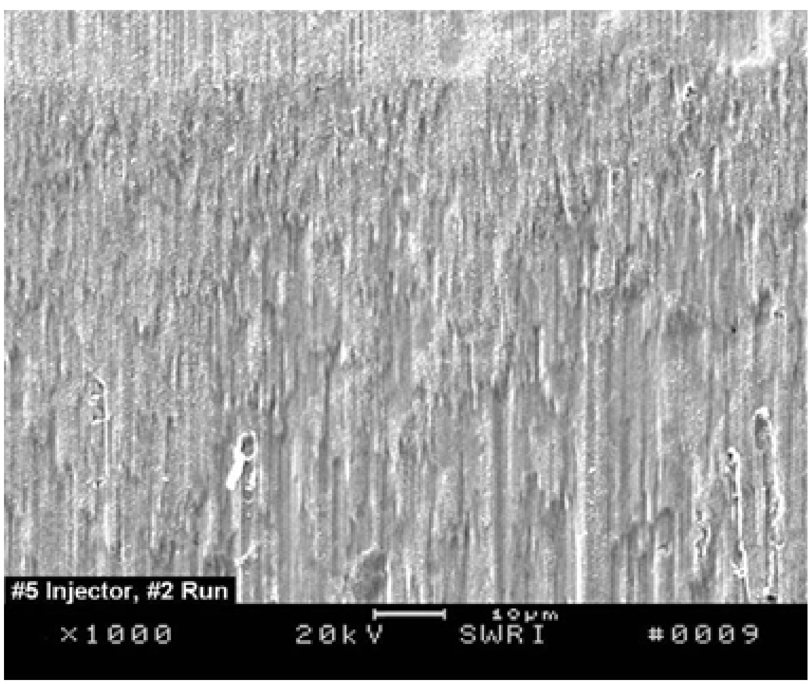


(b) s0681

Figure 14. Scanning electron micrographs of the inside surface of the sectioned injector bodies from (a) run 1, injector 1 and (b) run 2, injector 5. The sliding direction is vertical.

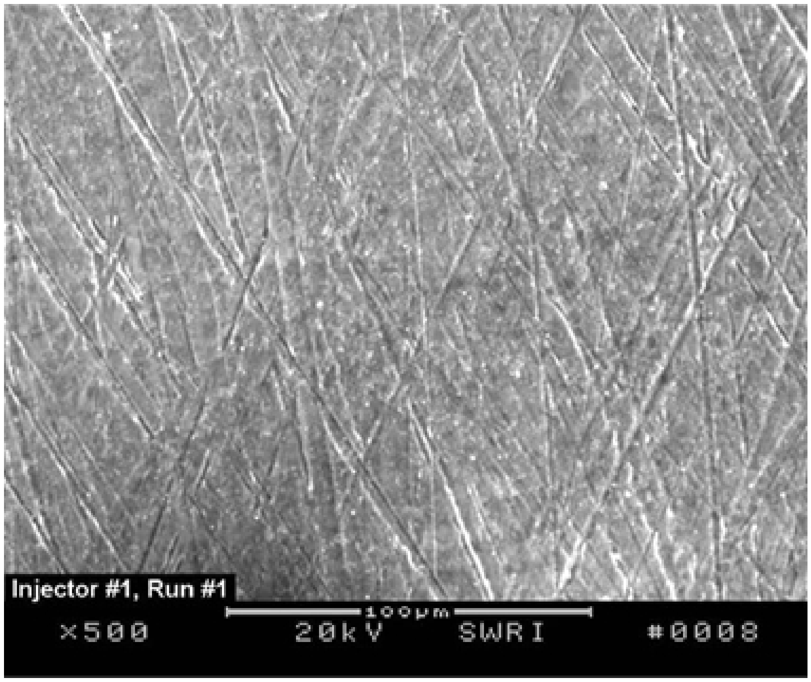


(a) s0678

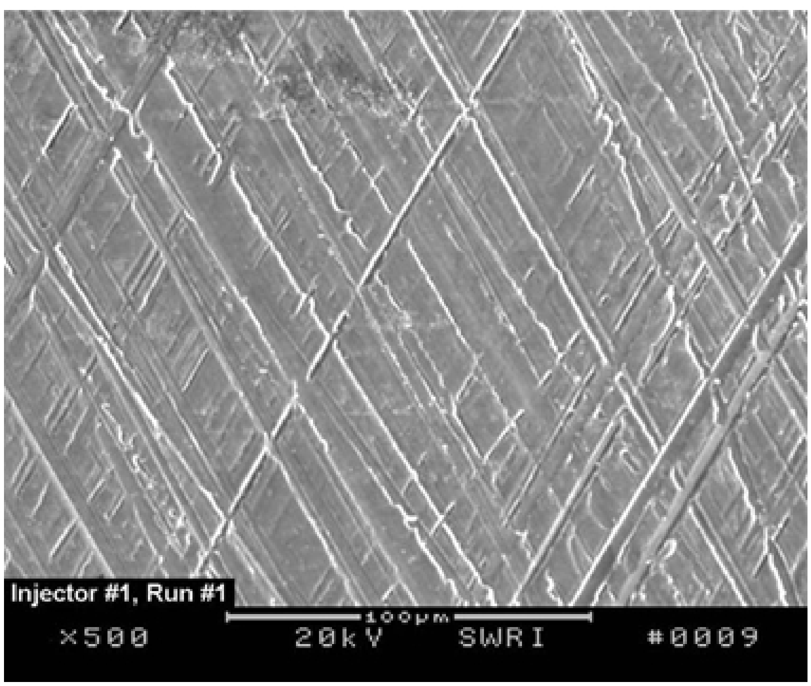


(b) s0682

Figure 15. Higher magnification SEM images from the inside surface of the sectioned injector bodies from (a) run 1, injector 1 and (b) run 2, injector 5. The sliding direction is vertical.

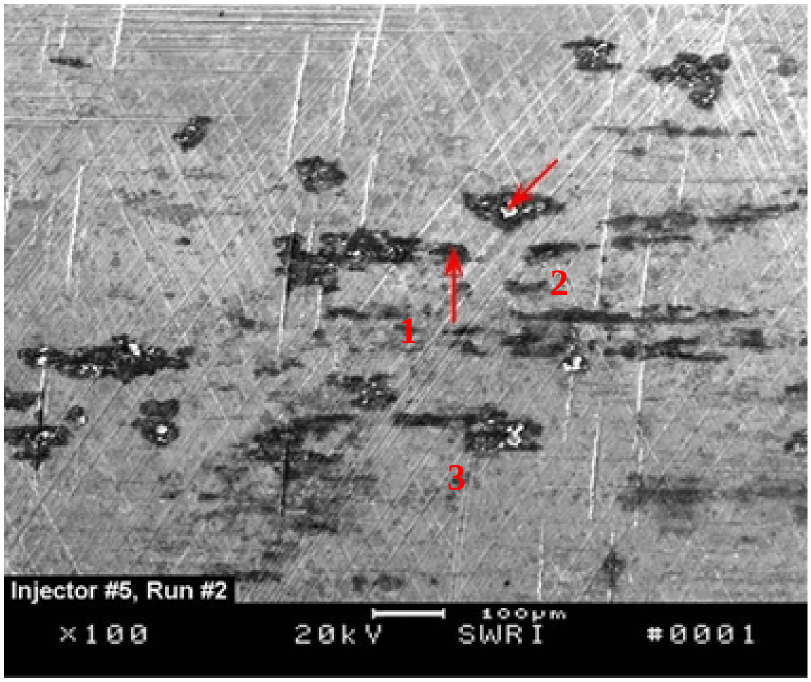


(a) s0692

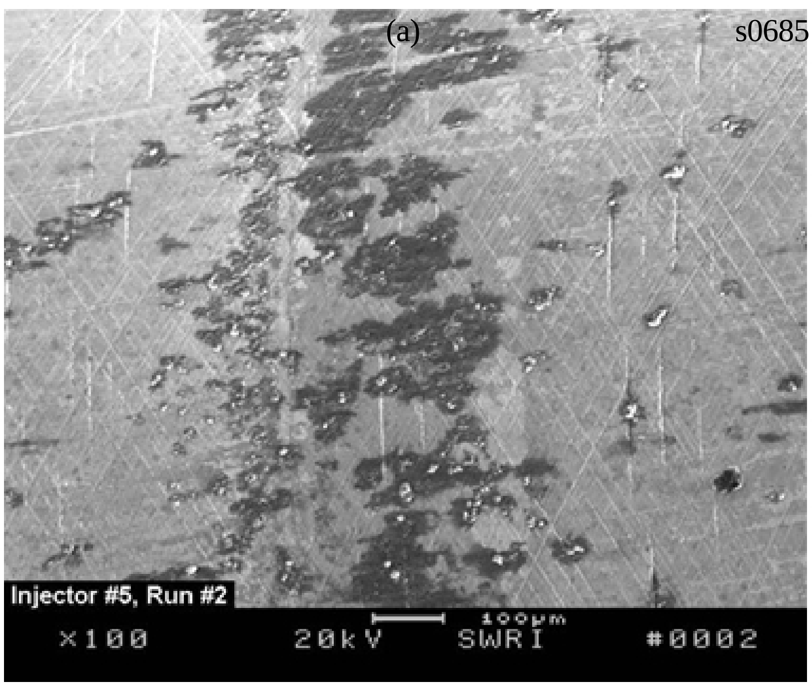


(b) s0693

Figure 16. SEM images of the inside surface of the run 1, injector 1 sectioned injector body from (a) within an etched appearing region and (b) outside of the etched appearing region.



(a) s0685



(b) s0680

Figure 17. SEM images of pitting present on the inside surface of the run 2,

injector 5 sectioned injector body. The sliding direction is horizontal.

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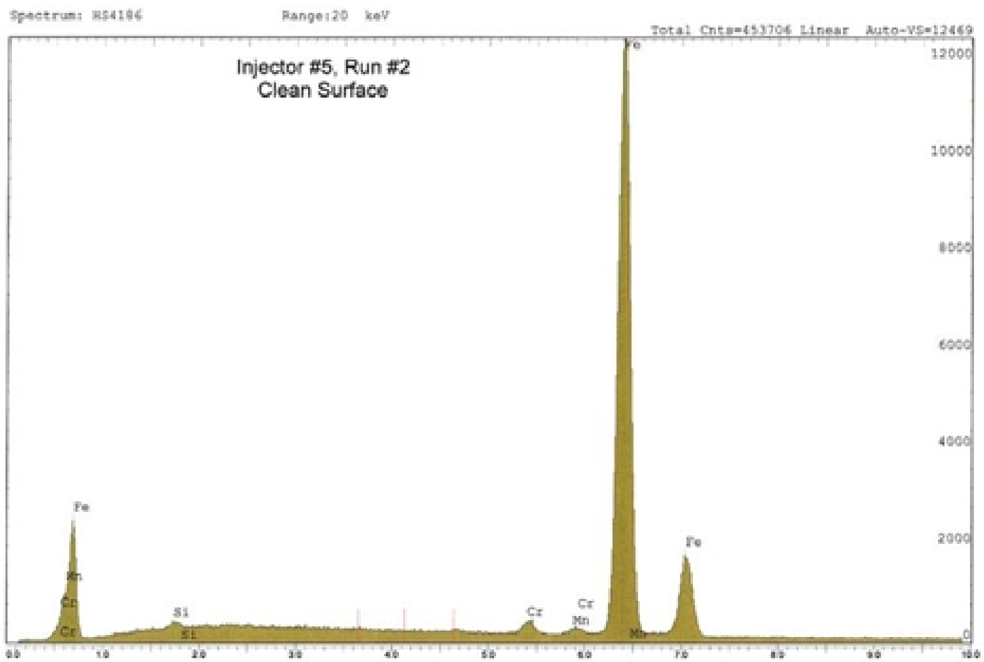

Figure 18. EDS spectrum from location 1 in Figure 17(a).

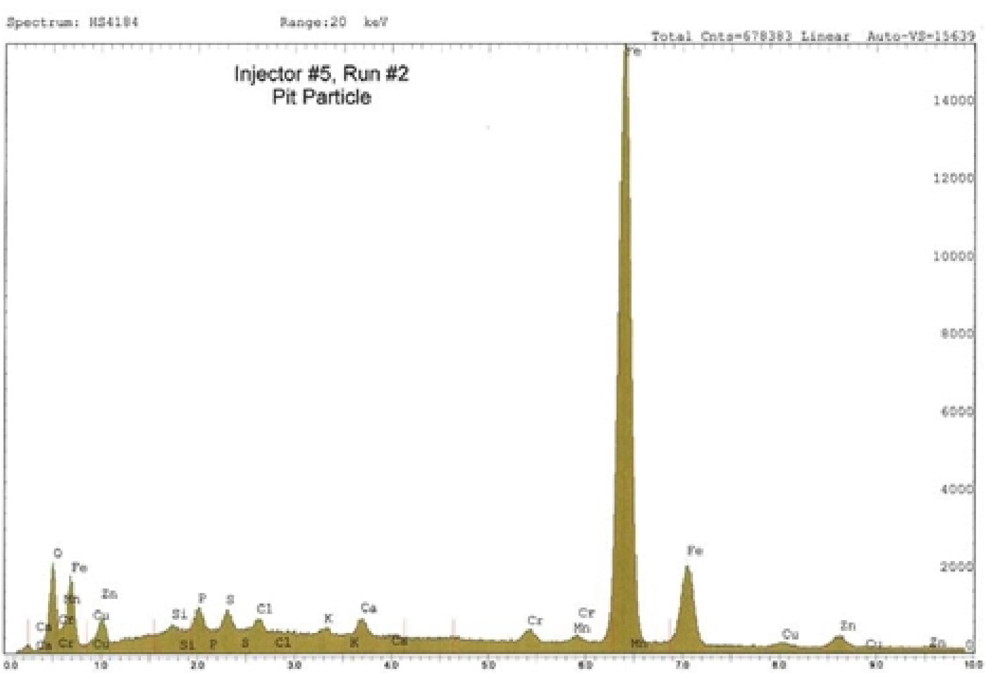

Figure 19. EDS spectrum from location 2 in Figure 17(a).

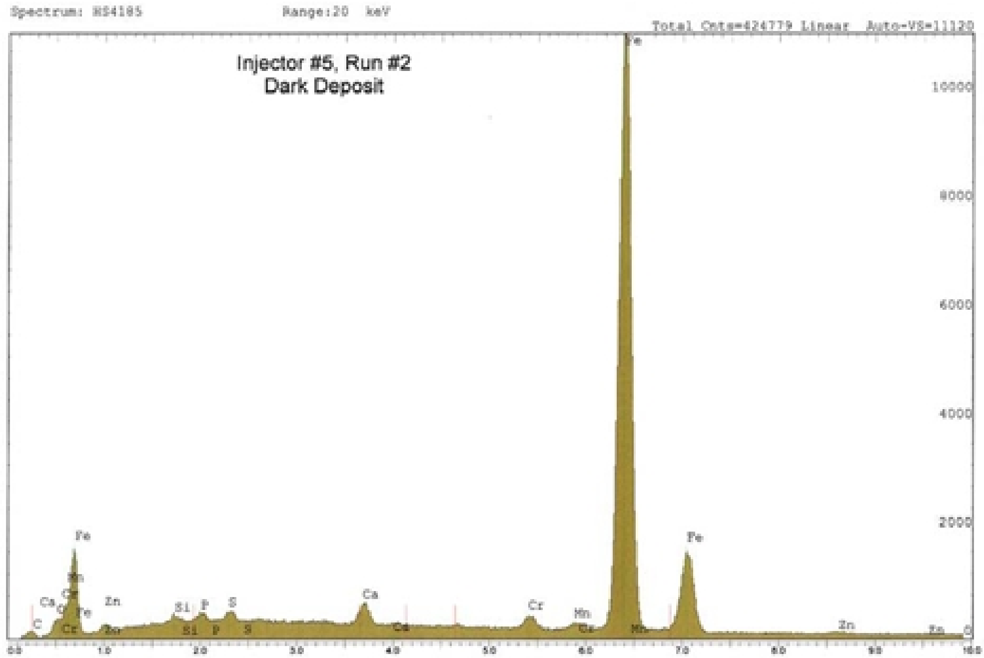

Figure 20. EDS spectrum from location 3 in Figure 17(a).

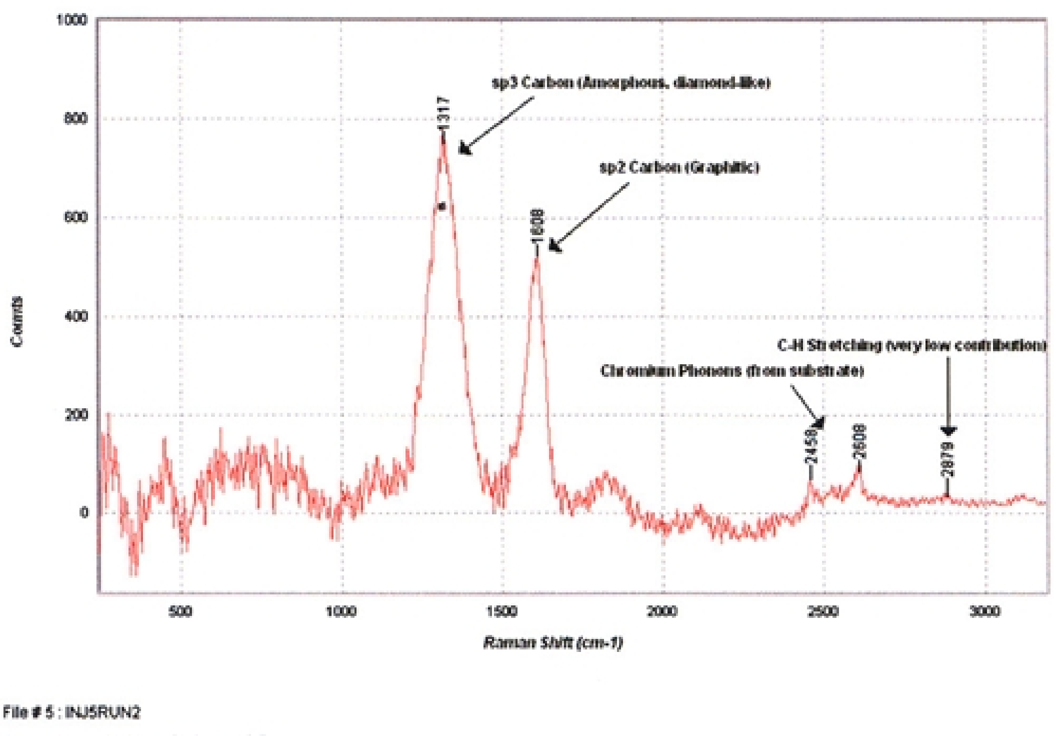

Figure 21. Raman spectrum obtained from the dark deposit present on portions of run 2, injector 5.

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